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PROGRESS REPORT

on

SIMULATION STUDY OF THE ROMPS ROBOT CONTROL SYSTEM

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REPORT SUMMARY

This is a report presenting the progress of a research grant funded by NASA for work performed from June 1, 1993 to August 1, 1993. The report deals with the Robot Operated Material Processing System (ROMPS). It presents results of computer simulation study conducted to investigate the performance of the control systems controlling the azimuth-, elevation- and radial-axes of the ROMPS robot and its gripper. Four study cases are conducted. The first case investigates the control of free motion of the three axes. In the second case, the compliant motion in the elevation axis with the wrist compliant device is studied in terms of position accuracy and impact forces. The third case focuses on the behavior of the control system in controlling the robot motion along the radial axis when pulling the pallet out of the rack. In the fourth case, the compliant motion of the gripper grasping a solid object under the effect of the gripper passive compliance is studied in terms of position accuracy and contact forces. For each of the above cases, a set of PIR gains will be selected to optimize the controller performance and computer simulation results will be presented and discussed.

1 Introduction

The Robot Operated Materials Processing System (ROMPS) has been developed at Goddard Space Flight Center (GSFC) under a flight project to investigate commercially promising in-space material processes and to design reflyable robot automated systems to be used in the above processes for low-cost operations [3]. The ROMPS is currently scheduled for flight in 1994 as a Hitchhiker payload in a Get Away Special (GAS) can. An important component of the ROMPS is a three degree-of-freedom (DOF) robot which will be responsible for carrying out the required tasks of in-space processing of selected materials. The mechanical interfaces and the compliant device of the ROMPS robot were tested using a six-degree-of-freedom (DOF) platform and the test results and recommendation can be found in [2]. This report deals with computer simulation study of the control systems to be implemented to control the motion of the three axes of the robot and the motion of its gripper. It is organized as follows. Section 2 presents the main components of the ROMPS robot and briefly describes the motion of each axis. Section 3 presents the study objectives and outlines the study cases. Modeling of the ROMPS robot is given in Section 4. Section 5 presents the stability analysis conducted for PIR and PR controllers. Results of computer simulation performed to investigate various axes of the ROMPS robot are reported in Section 6. Section 7 concludes the report with some comments and recommendations for future activities.

2 The ROMPS Robot

Figure 1 gives a sketch of the ROMPS which basically consists of a robot possessing three DOFs located in the center of the ROMPS, 148 pallets located around the robot on six racks and two ovens located at the top. The ROMPS side view is illustrated in Figure 2 showing the three axes of the ROMPS robot and its gripper. The axes are driven by brushless DC motors manufactured by Inland Motor Company. The elevation axis utilizes a roller screw to provide the elevation DOF defined as the vertical motion of the gripper. A rotary encoder is mounted on the motor shaft for elevation measurement. The azimuth DOF defined as the rotation about the elevation axis utilizes a rotary encoder mounted on the motor shaft and a 160:1 harmonic drive. The radial DOF defined as the *in-and-out* motion of the gripper is realized by an 1 mm lead ball screw and a linear encoder for displacement measurement. The gripper assembly mainly consists of two fingers equipped with Hall effect sensors and an Inland brushless motor driving a 50:1 harmonic drive with 1/4-16 acme screw. The assembly is mounted to the radial axis screw via a compliant device that provides passive compliance along the radial and elevation axes. As explained above the three DOFs and the gripper will enable the ROMPS robot to move the gripper to the vertical position of a pallet using the elevation and azimuth DOFs, to slide the gripper fingers into the pallet rack

using the radial DOF and then to grasp the pallet using the gripper fingers. The radial DOF will then enable the robot to slide the pallet out of the rack. The robot will then use the elevation and radial DOFs to take the pallet to a desired rack and place it there using the radial axis and the opening of the gripper fingers. Thus it is important to study the position control system to be used to control the axes and the gripper so that their gains can be set properly in order to ensure a successful mission of the ROMPS.

3 Study Cases

The four cases to be studied in this report are described below:

- **Study Case 1: Single Axis Motions in Free Space**
  This case investigates the decoupled motion of each single axis in free space. Each axis will be ramped up to maximum speed and ramped down to stop at a desired position. The controller gains will be adjusted until the position trajectory tracks the desired one within given accuracy specifications without overshoot and oscillations. In this case, reasonable steady velocity errors are acceptable. Observation will be made to find out if the acceleration and deceleration of the axes will excite the wrist compliant device enough to cause the gripper to oscillate. Consequently the spring mass model of the gripper and the compliant device will be derived to monitor possible oscillations during the acceleration and deceleration periods so that we can determine whether or not the compliant device bang against its hard stops.

- **Study Case 2: Compliant Motion of the Elevation Axis**
  The target position of the furnace to which the grasped pallet must be brought to may be shifted during launch or because of manufacturing error. If the target elevation is reduced, then the wrist compliant device can be used to compensate for the position error. It is also desired for the gripper to make a good contact with the furnace bottom by applying a specified contact force via the compliant device. This case studies the ability of the position control scheme of the elevation axis in reaching a target position and in applying a specified contact force in a compliant motion mode generated by the wrist compliant device. As illustrated in Figure 3, the elevation axis will be commanded to a position 1/8th of an inch past the location at which the gripper impacts the furnace bottom so that the compliant device is loaded to approximately 5 lb. It will be observed if oscillations occur at the time of impact. If oscillations occur, then we will determine if reduction in approaching velocity can help minimizing impact forces and oscillations.

- **Study Case 3: Radial Axis Motion under Resistance**
  This case studies the motion the radial axis performs in pulling out a pallet held in a rack under detent springs as illustrated in Figure 4. The radial axis will be commanded to pull out to free space. The pallet will initially resist the motion due to detent spring forces, then will break free and slides out under friction force against the rack. Observation will be made whether or not the control scheme is capable of overcoming the initial detent spring forces. The detent spring force will be modeled as a 5 lb threshold to break loose from the detents.

- **Study Case 4: Compliant Motion of the Gripper Finger**
  This case investigates the ability of the gripper fingers to grasp a solid object under a specified contact force. To do so, the gripper will be commanded to close on a solid object to a position 1/4th of an inch past the position at which the fingers first make contact with the object so that the gripper compliance device is loaded to about 10 lb. The control scheme for the gripper will be evaluated in terms of position and contact force accuracy.

4 Modeling of the ROMPS Robot

This section is devoted to developing the modeling equations for the ROMPS robot. First it shows the similarity and relationship between a general permanent magnet (PM) DC motor and the brushless DC motor used in the ROMPS robot. Modeling equations for a PM DC motor are then presented. After that, the overall transfer function matrices for PIR and PR controllers will be derived, respectively, and these transfer functions will be used in next section to determine the controller gains which ensure the system stability. Then vibrations caused by the wrist compliant device along the elevation and radial axes will be modeled using spring-mass systems. Finally motor load torque generated by pushing the gripper against the furnace bottom (Study case 3) will be modeled and computed.

4.1 Brushless DC Motor and PM DC Motor

The variables and parameters used for motors are first defined below:

i_a(t)	: armature current	L	: armature inductance
R	: armature resistance	e_a(t)	: armature voltage
e_b(t)	: back emf	K_b	: back-emf constant
T_L(t)	: load torque	ω_m(t)	: rotor angular velocity
T_m(t)	: motor torque	J_m	: rotor inertia of motor
θ_m(t)	: rotor displacement	B_m	: viscous-friction coefficient
K_t(t)	: torque constant	n	: number of poles
T_f	: maximum inertia torque (static friction and cogging torque)		

The motors used in the ROMPS robot are all brushless DC motors manufactured by the Inland Motor Company. After several discussions with an engineer of Inland Motor Company, it is concluded that the following equations describe the dynamic characteristics of a brushless motor:

$$e_a(t) = i_a\ R + \omega_m(t)\ K_b + L\ \tfrac{di_a}{dt} \tag{1}$$

$$L\ \tfrac{di_a}{dt} = L\ \frac{n}{\pi}\ i_a(t)\ \omega_m(t) \tag{2}$$

and

$$i_a(t) = \frac{T_L + T_f + B_m\omega_m(t)}{K_t} \tag{3}$$

On the other hand, a PM DC motor can be modeled by: [1]

$$e_a(t) = R\ i_a(t) + e_b(t) + L\ \tfrac{di_a}{dt} \tag{4}$$

$$T_m(t) = K_t\ i_a(t) \tag{5}$$

$$e_b(t) = K_b\ \omega_m(t) \tag{6}$$

and

$$T_m(t) = J_m \frac{d^2\theta_m(t)}{dt^2} + T_L(t) + B_m \frac{d\theta_m(t)}{dt} \tag{7}$$

Investigating Equations (3)-(7), we conclude that Equation (1) is equivalent to Equation (4) and Equation (3) is equivalent to Equation (7). In particular, we note that

$$T_f = J_m \frac{d^2\theta_m(t)}{dt^2} \tag{8}$$

Since we just show that the modeling equations for the brushless DC motor and PM DC motor are equivalent, from now on we use the modeling equations of PM DC motor to model the brushless motor.

4.2 State Equation Representation of PM DC motor

From Equations (4) - (7), the state representation of a PM DC motor is obtained as follows:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \quad (9)$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) \quad (10)$$

where

$\mathbf{x}(t) = [\ i_a(t) \quad \omega_m(t) \quad \theta_m(t)\ ]^T$ = state vector

$\mathbf{u}(t) = [\ e_a(t) \quad T_L(t)\ ]^T$ = input vector

$\mathbf{y}(t) = \theta_m(t)$ = output

and

$$\mathbf{A} = \begin{bmatrix} -\frac{R}{L} & -\frac{K_b}{L} & 0 \\ \frac{K_t}{J_m} & -\frac{B_m}{J_m} & 0 \\ 0 & 1 & 0 \end{bmatrix}, \ \mathbf{B} = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & -\frac{1}{J_m} \\ 0 & 0 \end{bmatrix}, \ \mathbf{C} = [\ 0 \quad 0 \quad 1\ ] \quad (11)$$

The output $\mathbf{y}(t)$ and the input vector $\mathbf{u}(t)$ are related by

$$\mathbf{Y}(s) = \mathbf{G}(s)\mathbf{U}(s) \quad (12)$$

where $\mathbf{Y}(s)$ and $\mathbf{U}(s)$ denote the Laplace transform of $\mathbf{y}(t)$ and $\mathbf{u}(t)$, respectively. $\mathbf{G}(s)$ is called the transfer function matrix which can be determined as: [1]

$$\mathbf{G}(s) = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} = \left[\ \frac{K_t}{\Delta_1(s)} \quad -\frac{R+Ls}{\Delta_1(s)}\ \right] \quad (13)$$

where

$$\Delta_1(S) = LJ_m s^3 + (RJ_m + LB_m)s^2 + (B_m R + K_t K_b)s \quad (14)$$

Using Equations (9)-(14), the DC motor can be represented in a block diagram as shown in Figure 5.

4.3 The Overall Transfer Function Matrix

Figure 6 illustrates the control system of the brushless DC motor. The control scheme consists of a proportional (P) controller, a switched integral (I) controller and a rate-feedback (R) controller. Rate-feedback controller is selected instead of derivative controller because of the improvement of the system damping. In the following, the overall transfer function matrices for the ramping period in which the I controller is *off* and for the steady-state period in which the I controller is *on* will be derived.

- **Case 1: PIR Controller (Steady-State Period)**

  The following development assumes that the integral controller is switched "on". From Equations (12) and (13), we obtain

$$\Theta(s) = \frac{K_t}{\Delta_1(s)} E_a(s) - \frac{R + Ls}{\Delta_1(s)} T_L(s) \quad (15)$$

  From Figure 6, $E_a(s)$ can be computed as

$$E_a(s) = [U_1(s) - K_f\Theta(s)]\,(K_P + \frac{K_I}{s}) - K_R K_f s\Theta(s) \quad (16)$$

where K_P, K_I and K_R denote gain matrices of the proportional, integral and rate controllers, respectively, and K_f is the roller screw constant. Substituting Equation (16) into (15) and solving for $\Theta(s)$, we obtain

$$\Theta(s) = \frac{(K_t K_P s + K_t K_I)U_1(s) - (Ls^2 + Rs)T_L(s)}{\Delta_2(s)} \tag{17}$$

where

$$\Delta_2(s) = s\Delta_1(s) + K_t K_R K_f s^2 + K_t K_f K_P s + K_t K_f K_I \tag{18}$$

From Equation (17), we can write

$$\Theta(s) = T_{PIR}(s) \begin{bmatrix} U_1(s) & T_L(s) \end{bmatrix}^T \tag{19}$$

where the overall transfer function matrix $T_{PIR}(s)$ is given by

$$T_{PIR}(s) = \begin{bmatrix} \frac{K_t K_P s + K_t K_I}{\Delta_2(s)} & -\frac{Ls^2 + Rs}{\Delta_2(s)} \end{bmatrix} \tag{20}$$

- **Case 2: PR Controller (Ramping Period)**

  In this case, we assume that the integral controller is switched "off" and the overall transfer function is derived as follows:

  For $K_I = 0$, $E_a(s)$ in Equation (16) becomes

$$E_a(s) = [U_1(s) - K_f\Theta(s)]\,K_P - K_R K_f s\Theta(s) \tag{21}$$

  Substituting Equation (21) into (15) and solving for $\Theta(s)$, we have

$$\Theta(s) = \frac{K_t K_P U_1(s) - (Ls + R)T_L(s)}{\Delta_3(s)} \tag{22}$$

  where

$$\Delta_3(s) = \Delta_1(s) + K_t K_R K_f s + K_t K_f K_P \tag{23}$$

  From Equation (22), we obtain

$$\Theta(s) = T_{PR}(s) \begin{bmatrix} U_1(s) & T_L(s) \end{bmatrix}^T \tag{24}$$

  where the overall transfer function matrix $T_{PR}(s)$ is given by

$$T_{PR}(s) = \begin{bmatrix} \frac{K_t K_P}{\Delta_3(s)} & -\frac{Ls + R}{\Delta_3(s)} \end{bmatrix} \tag{25}$$

4.4 Vibration Modeling

This section derives equations to model the gripper vibrations caused by the wrist compliant device. Vibrations can occur along the elevation axis and radial axis. The dynamics of the gripper assembly along the elevation axis can be modeled by a spring-mass system as illustrated in Figure 7.

Using Newton's second law, the equation of motion for the model in Figure 7 is obtained as

$$m_e(a_m + a_e) = -k_e x_1 \tag{26}$$

where

a_e : acceleration of the radial axis with respect to the robot base
a_m: acceleration of the gripper assembly with respect to the radial axis along the elevation axis
m_e: equivalent mass of the gripper assembly along the elevation axis
k_e : equivalent spring contant of the wrist compliant device along the elevation axis

In (26) replacing a_m by $\ddot{x_1}$ where x_1 denotes the displacement of the gripper assembly with respect to the radial axis yields

$$m_e\ddot{x_1} + k_e x_1 + m_e a_e = 0 \tag{27}$$

The dynamics of the gripper assembly along the radial axis is modeled by another spring-mass system as shown in Figure 8. Applying the same approach as in the case of elevation axis, the equation of motion for the radial axis is derived as

$$m_r\ddot{x_2} + k_r x_2 + m_r a_r = 0 \tag{28}$$

where

a_r : acceleration of the radial axis with respect to the base of the radial axis motor
a_m: acceleration of the gripper assembly with respect to the radial axis along the radial axis
m_r: equivalent mass of the gripper assembly along the radial axis
k_r : equivalent spring contant of the wrist compliant device along the radial axis

In the computer simulation to be conducted later, a_e and a_r in (27) and (28), respectively can be computed from Equation (7).

4.5 Modeling of the Motor Load Torque

This section is devoted to modeling and computing the motor load torque generated by the wrist compliant device when the robot gripper is pushed against the furnace bottom (Study Case 2) as illustrated in Figure 9. If the elevation axis is commanded to a position which is Δx bigger than the position at which the gripper makes the first contact with the furnace bottom, then the resulting elastic force generated by the wrist compliant device is transmitted to the elevation axis motor as a load torque. The load is computed by

$$T_L = K_f\ F_C = K_f\ k_e\Delta x \tag{29}$$

where F_C is the elastic force generated by the wrist compliant device along the elevation axis and K_f is the roller screw constant of the elevation axis.

Similar to Study Case 2, Study Case 4 requires the modeling and computation of the load torque generated by the gripper compliance spring when the gripper fingers are commanded to close on a solid object to a position which is Δx greater than the contact position. Using the same approach applied for the above case, the load torque transmitted to the gripper axis motor is computed by

$$T_L = K_f\ k_g\ \Delta x \tag{30}$$

where K_f denotes the ACME screw constant of the gripper axis and k_g, the spring constant of the compliance mechanism of the gripper fingers.

5 Stability Analysis

This section utilizes the Routh Hurwitz criterion to determine the controller gains which ensure the system stability. It comprises two parts. The first part deals with the PIR controller for steady-state period while the second part, the PR controller for ramping period.

- **Case 1: PIR Controller**

  The Routh array of $\Delta_2(s)$ for the PIR controller is given as follows:

$$
\begin{array}{llll}
s^4 & LJ_m & RB_m + K_tK_b + K_tK_fK_R & K_tK_fK_I \\
s^3 & LB_m + J_mR & K_tK_fK_P & \\
s^2 & W_1 & K_tK_fK_I & \\
s^1 & W_2 & & \\
s^0 & K_tK_fK_I & &
\end{array}
$$

where

$$W_1 = \frac{(LB_m+J_mR)(RB_m+K_tK_b+K_tK_fK_R) - LJ_mK_tK_fK_P}{LB_m+LEJmR}$$

$$W_2 = \frac{W_1K_tK_fK_P - (LB_m+J_mR)K_tK_fK_I}{W_1}$$

According to the Routh-Hurwitz stability criterion, for the system to be stable, the elements of the first column of the Routh array must be of the same sign. From the fact that all motor physical parameters must be positive, the first element LJ_m and the second element $LB_m + J_mR$ are obviously positive. Thus it is left to require that

$W_1 > 0$, $W_2 > 0$ and $K_tK_fK_I > 0$

From $W_1 > 0$, we derive

$$(LB_m + J_mR)(RB_m + K_tK_b + K_tK_fK_R) - LJK_tK_fK_P > 0$$

which results in

$$K_P < \frac{(LB_m + J_mR)(RF + K_tK_b + K_tK_fK_R)}{LJ_mK_tK_f} \tag{31}$$

From $W_2 > 0$, we obtain

$$W_1K_tK_fK_P - (LB_m + J_mR)K_tK_fK_I > 0$$

which results in

$$(LB_m+J_mR)(RB_m+K_tK_b+K_tK_fK_R)K_tK_fK_P > LJ(K_tK_fK_P)^2+(LB_m+J_mR)^2K_tK_fK_I \tag{32}$$

Finally from $K_tK_fK_I > 0$, since $K_t > 0$ and $K_f > 0$, it is required that

$$K_I > 0 \tag{33}$$

The inequalities given in Equations (31), (32) and (33) will be used to select K_P, K_I and K_R to ensure the system stability.

- **Case 2: PR Controller**

  The Routh array for the PR controller can be readily obtained by simply setting $K_I = 0$ in the above Routh array that was obtained for the PIR controller. Consequently the Routh Array of $\Delta_3(s)$ is given as follows:

$$
\begin{array}{lll}
s^3 & LJ_m & RB_m+K_tK_b+K_tK_fK_R \\
s^2 & LB_m+J_mR & K_tK_fK_P \\
s^1 & W_1 & \\
s^0 & K_tK_fK_P &
\end{array}
$$

Inspecting the above Routh array, in order to ensure the system stability, it is required that $W_1 > 0$ and $K_t K_f K_P > 0$. As in the case of PIR controller, the inequality $W_1 > 0$ yields the inequality given in (31). Furthermore from $K_t K_f K_P > 0$, since $K_T > 0$ and $K_f > 0$, it is also required that

$$K_P > 0 \tag{34}$$

The inequalities given in Equations (31) and (34) will be used to select K_P and K_R that ensure the system stability.

6 Computer Simulation Study

This section reports the results of the computer simulation study conducted to investigate the performance of the ROMPS control system using a simulation software called the System Simulation Language (SYSL) [4].

6.1 Motor Parameters

The parameters used in the computer simulation are tabulated below.

Parameters	Units	Elevation	Azimuth	Radial	Gripper
J	$oz \cdot in \cdot sec^2$	4.9×10^{-3}	1.2×10^{-3}	2.67×10^{-5}	1.3×10^{-4}
L	$H(\frac{V\cdot sec}{amp})$	1.8×10^{-3}	1.4×10^{-3}	0.55×10^{-3}	1.2×10^{-3}
F	$\frac{oz\cdot in}{rpm}$	1.7×10^{-3}	3.5×10^{-4}	1.24×10^{-5}	6.9×10^{-5}
F	$\frac{oz\cdot in\cdot sec}{rad}$	1.62×10^{-2}	3.34×10^{-3}	1.1841×10^{-4}	6.589×10^{-4}
R	ohms	2.5	2.9	3.86	3.7
K_b	$\frac{V\cdot sec}{rad}$	0.169	0.0886	0.016	0.034
K_f	$\frac{in}{rad}$	0.01253	0.04377	6.2659×10^{-4}	1.9894×10^{-4}
K_T	$\frac{oz\cdot in}{amp}$	24.0	12.5	2.2	4.8
Max_curr	amp	1.5	1.4	0.45	1.0
Max_spd	$\frac{in}{sec}$	1.7087	11.4675	0.9252	0.135

Table 1: Motor parameters.

In Table 1, Max_curr and Max_spd denote the maximum current and speed, respectively. The calculations of K_f and Max_spd for each study case are given in Appendix A and Appendix B. The maximum voltage, Max_volt used in the computer simulation study is 28 volts.

6.2 Trajectory Planner

In the computer simulation, the time trajectories of the desired motor velocity and displacement are generated by a trajectory planner. The subroutine Profile implementing the trajectory planner (Figure 10) produces a control position trajectory and a control speed trajectory based upon the targetPosition and the maxSpeed supplied by the user as described as follows. When a "move" command is initiated, Profile subroutine sets the control speed either to +maxSpeed or -maxSpeed depending on the desired direction of motion. It also sets the controlPosition to the current position of the axis. Then on each successive five msec cycle, it adds controlSpeed to controlPosition, causing the controlSpeed to stairstep (ramp) toward targetPosition (Figure 11). The Profile subroutine also produces a boolean value which is 0 when the controlPosition is ramping and 1 when the ramping is finished (steady-state). This boolean value serves a switch to turn off (boolean value=0) and on (boolean value=1) the I controller as shown in Figure 6.

6.3 Simulation Results and Discussions

This section presents and discusses results obtained from the computer simulation conducted for Study Cases 1-4.

6.3.1 Study Case 1:

As stated before, the objective of this study case is to investigate the decoupled motion of each single axis in free space. Thus each axis will be ramped up to maximum speed and ramped down to stop at a desired position.

- **Elevation Axis:** Starting at zero displacement, the elevation axis is ramped up with a constant velocity Max_spd = 1.7087 $\frac{in}{sec}$ to reach a displacement of 18 in. at t = 10.5343 sec. After staying at 18 in. for five seconds, it is ramped down with a constant velocity of -1.7087 ($\frac{in}{sec}$) to reach a new desired displacement of -18 in. Figure 1.1.1(a) and 1.1.1(c) show the time trajectories of the controlSpeed and phase, respectively. Figure 1.1.2(a) shows the controlPosition. The PIR controller gains were first selected to satisfy the stability conditions specified by the inequalities given in Section 5. They were then fine tuned using the *cut and try* method until the best response was achieved. Starting from $K_P = 80$, $K_I = 0.01$ and $K_R = 15$, we found that increasing in K_I and K_R has negligible effects on the response while a change in K_P has significant effect on the response. The set of PIR gains K_P=440, K_I=0.01 and K_R=15 which yield the best response are listed in Table 2. Figures 1.1.1.(b) and (c) illustrate the corresponding actual displacement and tracking error. We note that the maximum tracking error is 0.113 inch (0.63%) that is far less than the specified accuracy requirement of 5 %.

  Figures 1.1.3 displays the gripper vibrations caused by the compliant device along the elevation axis during the above motion. We note that the vibration amplitude is less than 4.0 $\times 10^{-2}$ in. From the fact that hard stop travel along the elevation axis is about 0.25 inch, we conclude that the vibration in this case does not cause the compliant device to bang against its hard stops. After running numerous simulations with various set of PIR gains, we find as expected that the I controller reduces the steady state error and the R controller adds damping to the response. In addition, we observe that the P controller has the greatest impact on the behavior of the tracking error.

- **Azimuth Axis:** Starting at zero displacement, the azimuth axis is ramped up with a constant velocity of Max_spd=11.4675 $\frac{in}{sec}$ to reach a displacement of 44 in. at t = 3.8369 sec. and stays there for five seconds. Then it is ramped down with a constant velocity of -11.4675 $\frac{in}{sec}$ to reach a new desired displacement of -44 in. The set of PIR gains providing the best response with a maximum tracking error of 0.1569 in. (0.36%) is given in Table 2. Figures 1.2.1 and 1.2.2 show the trajectories generated by the trajectory planner and the actual response tracking error.

- **Radial Axis:** Figures 1.3.1 and 1.3.2 display the trajectories generated by the trajectory planner, the actual response and tracking error when the radial axis is commanded to ramp up and down to ± 4 in. with a constant velocity of $\pm$ Max_spd = 0.9252 $\frac{in}{sec}$. The set of PIR gains yielding the best response with a maximum of 0.041 in. (1%) is given in Table 2. Figure 1.3.3 shows the gripper vibration along the radial axis during the free motion. The figure reveals that the vibration amplitude is less than 5.0×10^{-3} in. Thus the vibration in this case does not cause the compliant device to bang against its hard stops since the hard stop travel of the compliant device is about 0.25 inch along the radial axis.

- **Robot Gripper:** Figures 1.4.1 and 1.4.2 display the results obtained when the gripper is ramped up and down to ± 0.4 in. with a constant velocity of $\pm$ Max_spd = 0.135 $\frac{in}{sec}$. The set of PIR gains yielding the best response with a maximum tracking error of 0.03266 in. (4.67%) is given in Table 2.

6.3.2 Study Case 2:

The objective of this study case is to investigate the ability of the elevation axis control scheme in reaching a target position and in applying a desired contact force on the oven bottom in a compliant motion mode caused by the wrist compliant device. Thus the elevation axis is commanded to a position $\frac{1}{8}$ of an inch past the position at which the gripper impacts the furnace bottom plate. Since the equivalent spring constant of the wrist compliant device along the elevation axis is 52 lb/in., the desired contact is 6.5 lb. The analysis done in Section 4.5 is incorporated in the computer simulation of this case. The set of PIR gains which yield a minimum tracking error and contact force error are $K_P = 900$, K_I=0.01, K_R=.015, as given in Table 2. The corresponding trajectories of speed, position, phase and tracking error are displayed in Figure 2.1 and 2.2. Figure 2.3(a)-(b) show the trajectories of the displacement of the compliant device center with respect to the contact point (the contact point is the zero line) and the impact force, respectively. The impact force is computed by F $= k_e \cdot (pos - x)$ where *pos* denotes the elevation position of the radial axis (see Figures 7 and 9) (the zero line of pos on Figure 2.2(b) indicates the contact point) and x denotes the displacement of the compliant device center with respect to the contact point. As seen in Figure 2.3(b), the impact force oscillates between 2 and 10 lbs. Figure 2.4 shows the trajectories of the compliant device center and the impact force when the approaching velocity is reduced to 0.7087 $\frac{in}{sec}$. Figure 2.4(b) shows that force oscillation is reduced substantially.

Figure 2.5 shows the trajectories of the desired position, actual position and position tracking error when the gains used in Study Case 1 for the elevation axis, namely, $K_P = 440$, K_I=0.01, K_R=15 are applied with an approaching velocity of 1.7087 $\frac{in}{sec}$. The output position reaches its desired position of 0.125 in. with larger tracking error caused by the larger time it takes to reach the target position. Since the steady error in this case is zero, we conclude that the same set of gains as used in Study Case 1 for the elevation axis can be used for Study Case 2.

6.3.3 Study Case 3:

As stated before in Section 3, the objective of this study case is to investigate the ability of the radial axis control system in pulling out a pallet held in a rack under detent springs. Thus the radial axis is commanded to pull a pallet out of the rack to free space for a travel of one inch. The pallet will initially resist the motion due to detent spring forces resulting in an extension of the spring mass model along the radial axis. The pallet will break free as soon as a resistant force reaches 5 lbs. The effect of the force caused by the detent springs can be modeled by including an initial displacement as an initial condition in the solution of the differential equation given in Equation (28). The initial displacement is computed by $X_0 = \frac{F}{k_r} = \frac{5}{68} = 7.353\times10^{-2}$(inch). For this case, we use the same set of controller gains used in Study Case 1 for the radial axis, namely K_P=680, K_I=0.01, K_R=0.01 to pull the pallet out for one inch. Sliding friction caused by the rack is ignored in the computer simulation. Figures 3.1 and 3.2 show the trajectories of desired speed and position, phase, actual position and position tracking error. Figure 3.3 shows the oscillation of the gripper assembly along the radial axis after breaking free from the detent springs. As seen in the figure, since the oscillation amplitude is about 0.075 inch we conclude that the oscillation does not cause the wrist compliant device to bang against its hardstop whose travel is about 0.25 inch.

6.3.4 Study Case 4:

The objective of this study case is to investigate the ability of the gripper fingers in grasping a solid object with a desired grasping force. Thus the gripper is commanded to close on a solid object 1/4th of an inch past the contact position so that approximately 10 lb of grasping force is generated. Ignoring the mass of the finger compliance mechanism, Equation (30) is modified to compute the gripper motor load torque. Thus the load torque T_L is computed by $k_g \cdot pos \cdot K_f$ instead of $T_L = k_g \cdot (pos - x) \cdot K_f$ by ignoring the oscillation of the finger (letting $x = 0$). The same set of controller gains used in Study Case 1 for the gripper axis is used in this case. Figures 4.1-4.3 show the computer simulation results. Figure

4.1(c) indicates that the maximum tracking error is 0.0319 in. and the steady tracking error is zero. Figure 4.3 shows that the grasping force reaches its steady state value of 10 lb. after about 2 seconds.

Study Case	Axis	K_P	K_I	K_R	Max. error(in)	Max. error in %
1	Elevation	440	0.01	15	0.113	0.63
1	Azimuth	150	10	0.01	0.1569	0.36
1	Radial	600	0.01	0.01	0.0401	1.00
1	Gripper	720	0.001	0.15	0.03266	4.67
2	Elevation	900	0.01	0.015	0.00131	1.04
2	Elevation	440	0.01	15	0.05427	43.42
3	Radial	600	0.01	0.01	0.0401	4.01
4	Gripper	720	0.001	0.15	0.0319	12.76

Table 2: Controller gains and tracking errors

7 Conclusions and Future Work

This report has dealt with modeling and control of the ROMPS robot. Four study cases were conducted to study the control performance of the elevation, radial, azimuth axes and the robot gripper in various scenarios. The equations of motion of a permanent magnet DC motor was employed to model the brushless DC motor to be used in actuating the robot axes. Modeling of vibrations along the elevation and radial axes, caused by the robot wrist compliant device was performed using spring-mass models. Load torques generated by the wrist compliant device and the finger compliance mechanism were computed. Using Routh Hurwitz method, stability analysis was conducted for proper selection of the controller gains which ensure the closed-loop system stability. To conclude this report, we would like to present the following observations and recommendations:

- **Stability Analysis**
  Although a careful stability analysis was conducted for the gain selection ensuring the system stability, we should be aware of the following. System stability implies that the error will decay to zero, but does not control the transient behavior of the responses. Consequently, in order to achieve a desired behavior of the transient response, *cut and try* method should be employed to select the controller gains.

- **Gain Selection**
  Simulation results showed that the same set of PIR gains used for free motion control (Study Case 1) can be used to give satisfactory performance in compliant motion as in Study Cases 2, 3 and 4. Consequently it is not necessary to change the controller gains when going from free motion to compliant motion, and vice versa.

- **Future Simulation Study**
  We learned after working intensively with SYSL that the most time consuming part of the computer simulation study is the coding of the modeling equations, running the resulting programs and debugging it. SYSL is especially sensitive to initial conditions and sampling rates. As a result, we would like to recommend that future computer simulation study be conducted using a simulation package that requires minimal coding such as Matlab/Simulink.

- **Advanced Control Schemes**
  The stability analysis using the Routh Hurwitz method provides a way to select a set of PIR gains which ensure the system stability for a set of parameters and conditions of the motor, robot and

environment. The controller gains are fixed and therefore may not provide good performance if the parameters and conditions are changed. We would like to recommend that advanced control schemes such as adaptive control, learning control and fuzzy control, etc. be used for the next generation of ROMPS robot. This type of advanced control schemes are able to adjust their controller gains to effectively adapt to the changes in the system parameters and environment.

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[4] **SYSL User's Guides**, System Simulation Language, Version 3, E^2 *Consulting*, California, December 1992.

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APPENDIX A
Calculation of the Screw Constant K_f

The computation of the screw constant K_f for various axes of the ROMPS robot axes is given below:

- **Elevation Axis:**
  $K_f = \frac{0.07874(\frac{inch}{rev})}{2\pi} = 0.01253(\frac{inch}{rad})$

- **Azimuth Axis:**
  $160\ revolutions\ (revs) \equiv 44\ inches\ (inch)\ for\ full\ scale$
  $K_f = \frac{44}{160 \times 2\pi} = 0.04377(\frac{inch}{rad})$

- **Radial Axis:**
  $K_f = \frac{0.03937(\frac{inch}{rev})}{10 \times 2\pi} = 6.2659 \times 10^{-4}(\frac{inch}{rad})$

- **Gripper Axis:**
  $560\ revs \equiv 0.7 inch\ for\ full\ scale$
  $K_f = \frac{0.7}{560 \times 2\pi} = 1.9894 \times 10^{-4}(\frac{inch}{rad})$

APPENDIX B
Calculation of the Maximum Speed Max_spd

This appendix provides the calculation of the maximum speed of various motors used in the ROMPS robot. The parameters needed for the computation are tabulated for each motor in the following table which also shows the calculation results:

	motor scale const	angular max speed	gear ratio	linear max speed(Max_spd)
Units	$(\frac{inch}{rev})$	$(\frac{rev}{sec})$	$(---)$	$(\frac{inch}{sec})$
Elevation	0.07874	21.7	1:1	1.7087
Azimuth	44	41.7	160:1	11.4675
Radial	0.03937	235	10:1	0.9252
Gripper	0.0625	108	50:1	0.135

The detailed calculations of the the linear maximum speeds are given below:

1. **Elevation Axis:**
   With 228.6 revs $\equiv$ 18 inches for full travel, the motor scale constant is computed by
   $\frac{18\ inch}{228.6\ rev} = 0.07874(\frac{inch}{rev})$
   Thus the linear maximum speed is computed as
   $Max\_spd = 21.7(\frac{rev}{sec}) \times 0.07874(\frac{inch}{rev}) = 1.7087(\frac{inch}{sec})$.
2. **Azimuth Axis:**
   With 160 revs $\equiv$ 44 inches for full travel, through a 160:1 harmonic drive, the motor scale constant is computed by
   $\frac{44\ inch}{\frac{160\ rev}{160}} = 44(\frac{inch}{rev})$
   Thus the linear maximum speed is obtained as
   $Max\_spd = 41.7(\frac{rev}{sec}) \times \frac{1}{160} \times 44(\frac{inch}{rev}) = 11.4675(\frac{inch}{sec})$.
3. **Radial Axis:**
   With 1016 revs $\equiv$ 4 inches for full travel through a 10:1 harmonic drive, the motor scale constant is obtained as
   $\frac{4\ inch}{\frac{1016\ rev}{10}} = 0.03937(\frac{inch}{rev})$
   Thus the linear maximum speed is computed by
   $Max\_spd = 235(\frac{rev}{sec}) \times \frac{1}{10} \times 0.03937(\frac{inch}{rev}) = 0.9252(\frac{inch}{sec})$.
4. **Gripper Axis:**
   With 560 revs $\equiv$ 0.7 inch for full travel, through a 50:1 Harmonic drive, the motor scale constant is computed by
   $\frac{0.7\ inch}{\frac{560\ rev}{50}} = 0.0625(\frac{inch}{rev})$
   Thus the linear maximum speed is computed as
   $Max\_spd = 108(\frac{rev}{sec}) \times \frac{1}{50} \times 0.0625(\frac{inch}{rev}) = 0.135(\frac{inch}{sec})$.

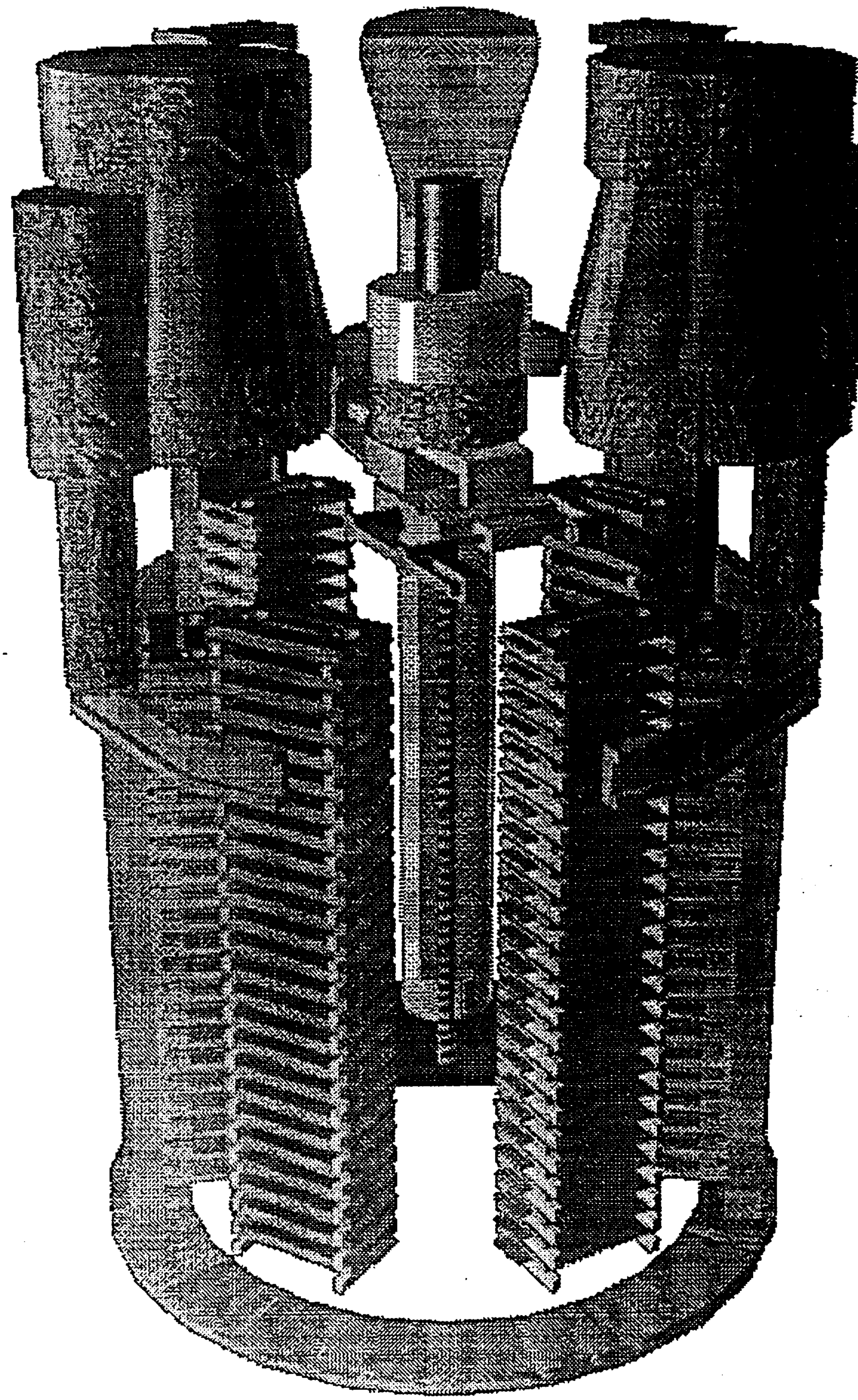

Figure 1 The Robot Operated Materials Processing System (ROMPS)

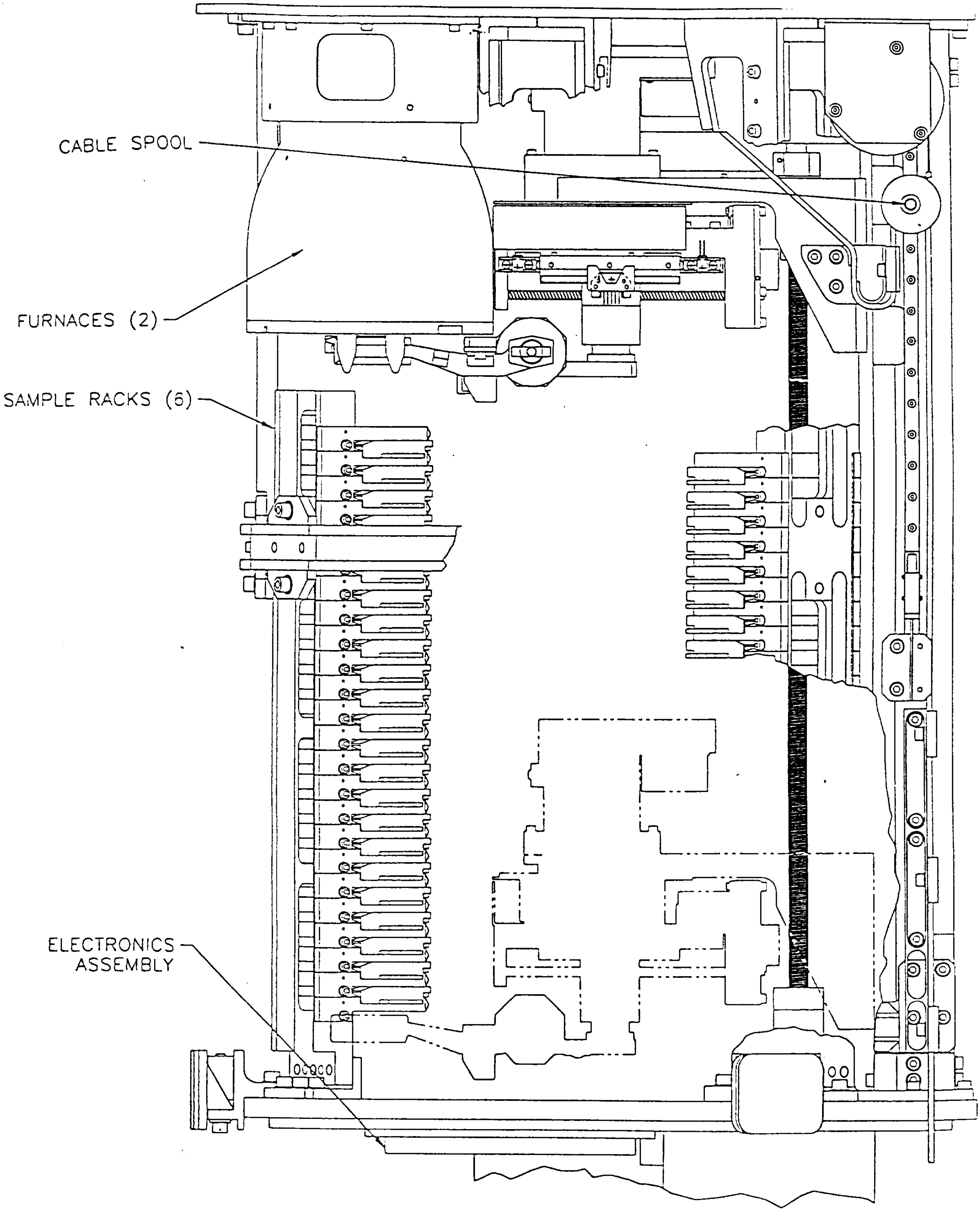

Figure 2 Side view of the ROMPS robot

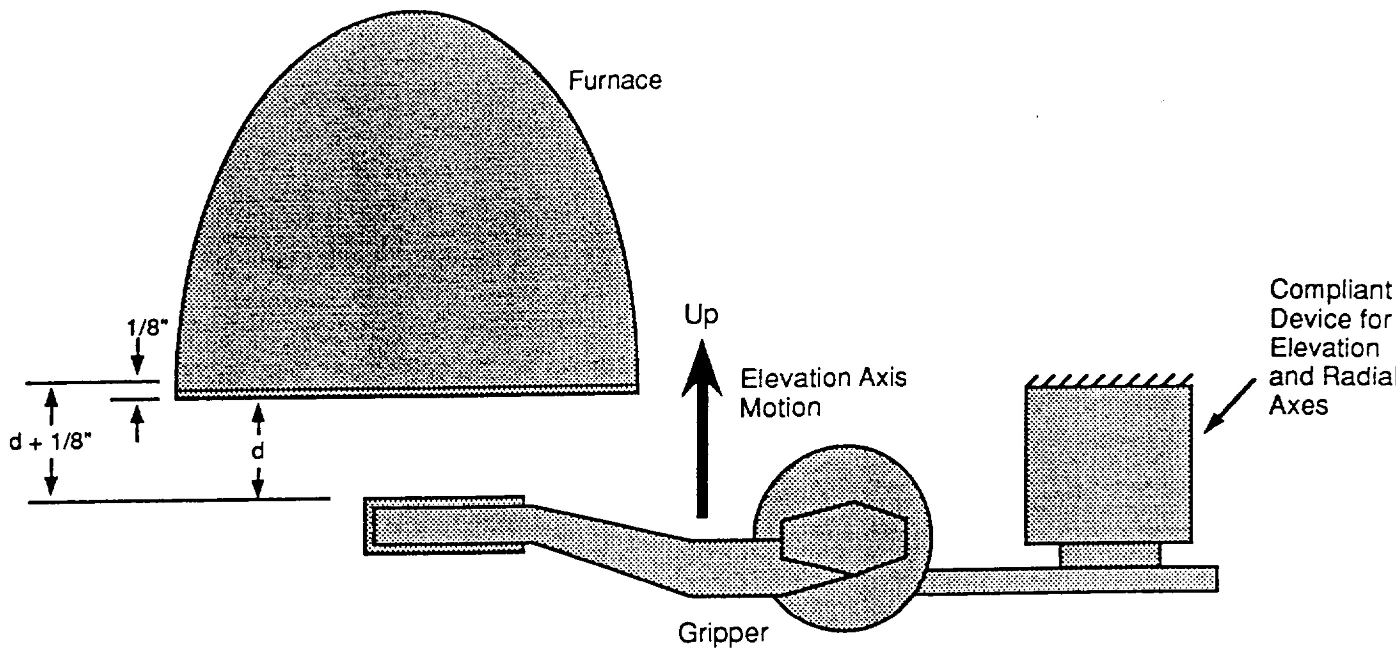

Figure 3 Study of the compliant motion of the elevation axis (Study Case 2)

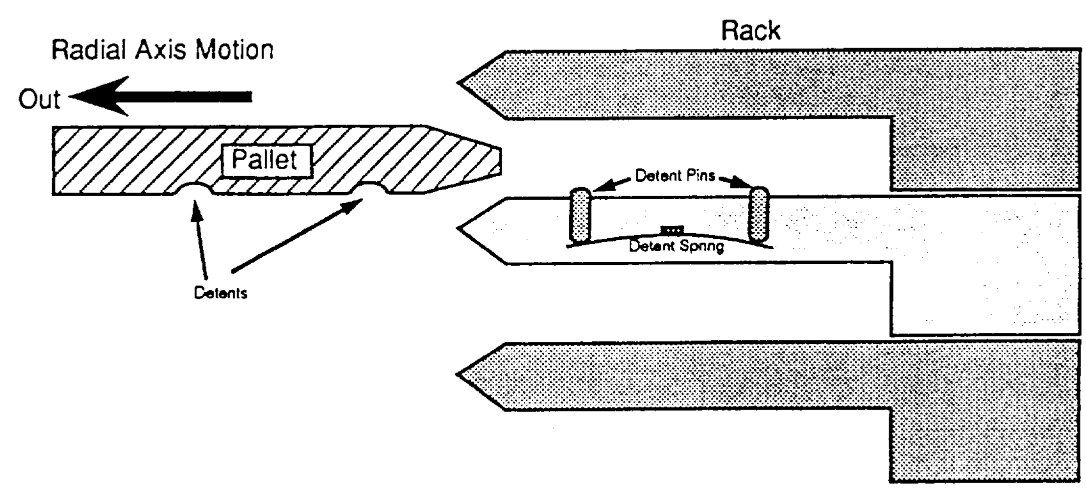

Figure 4 Study of the compliant motion of the radial axis (Study Case 3)

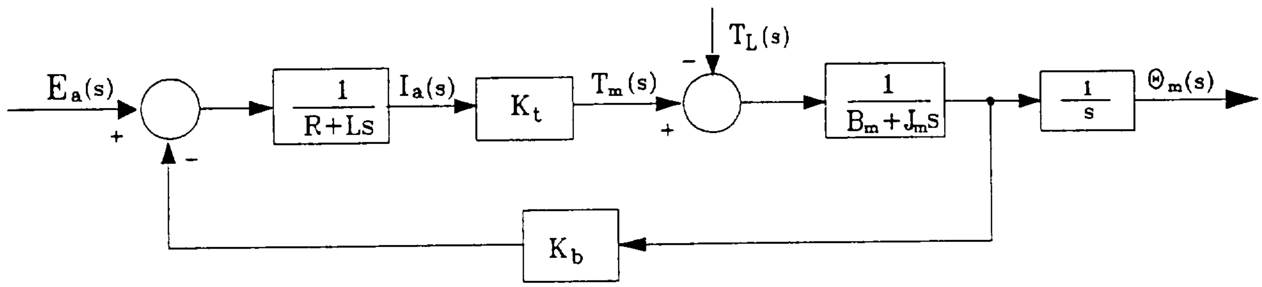

Figure 5 Block diagram of the DC motor

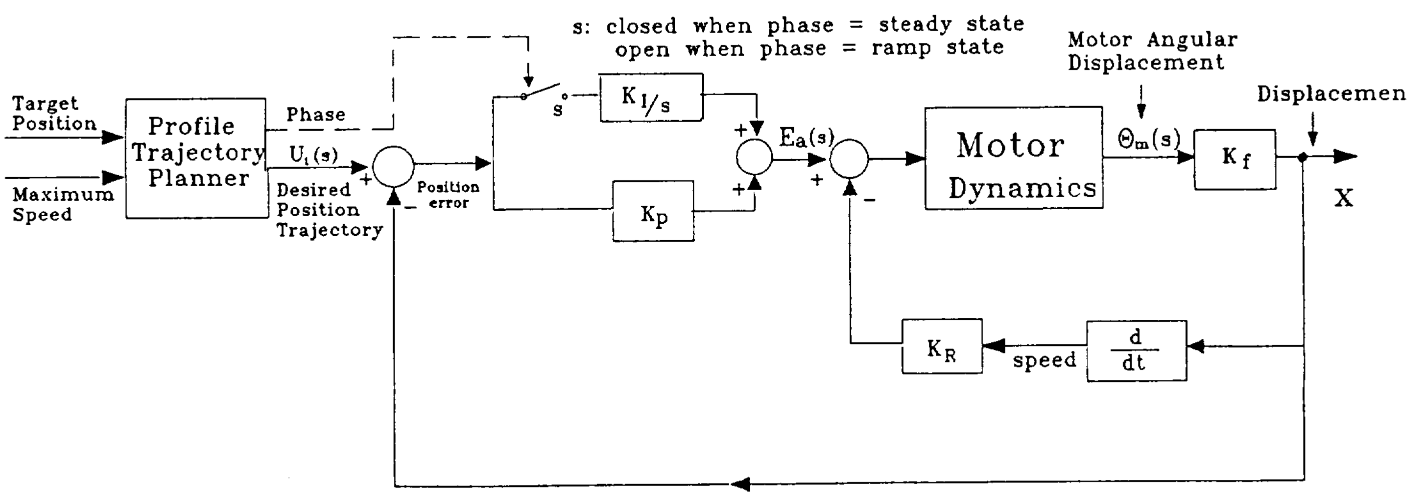

Figure 6 Control system of the brushless DC motor

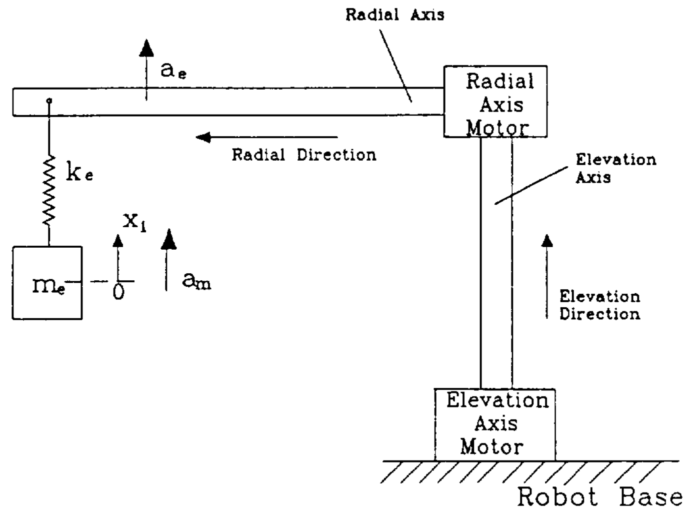

Figure 7 Modeling of the vibration along the elevation axis

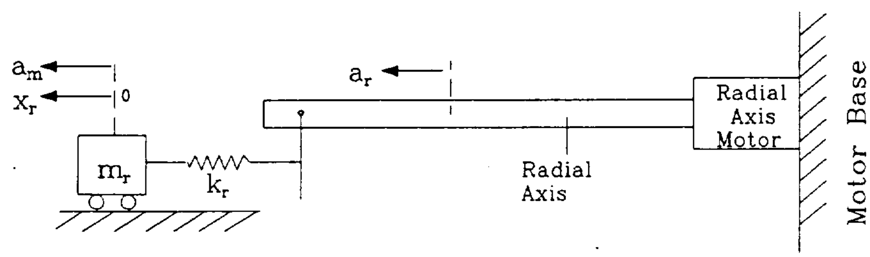

Figure 8 Modeling of the vibration along the radial axis

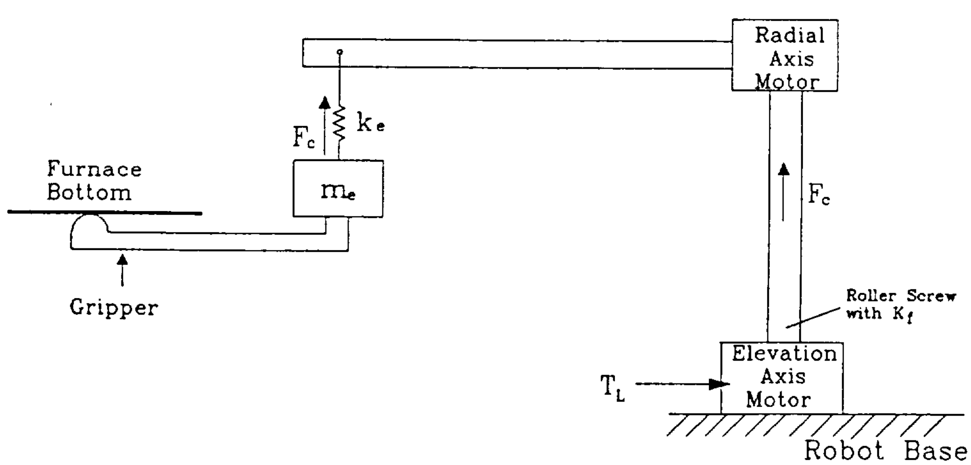

Figure 9 Modeling of the motor load torque

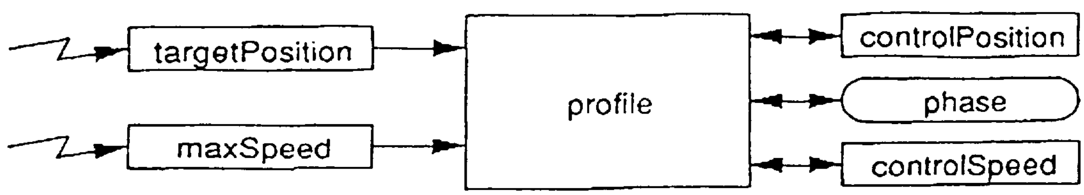

Figure 10 Block diagram of the trajectory planner subroutine (Profile)

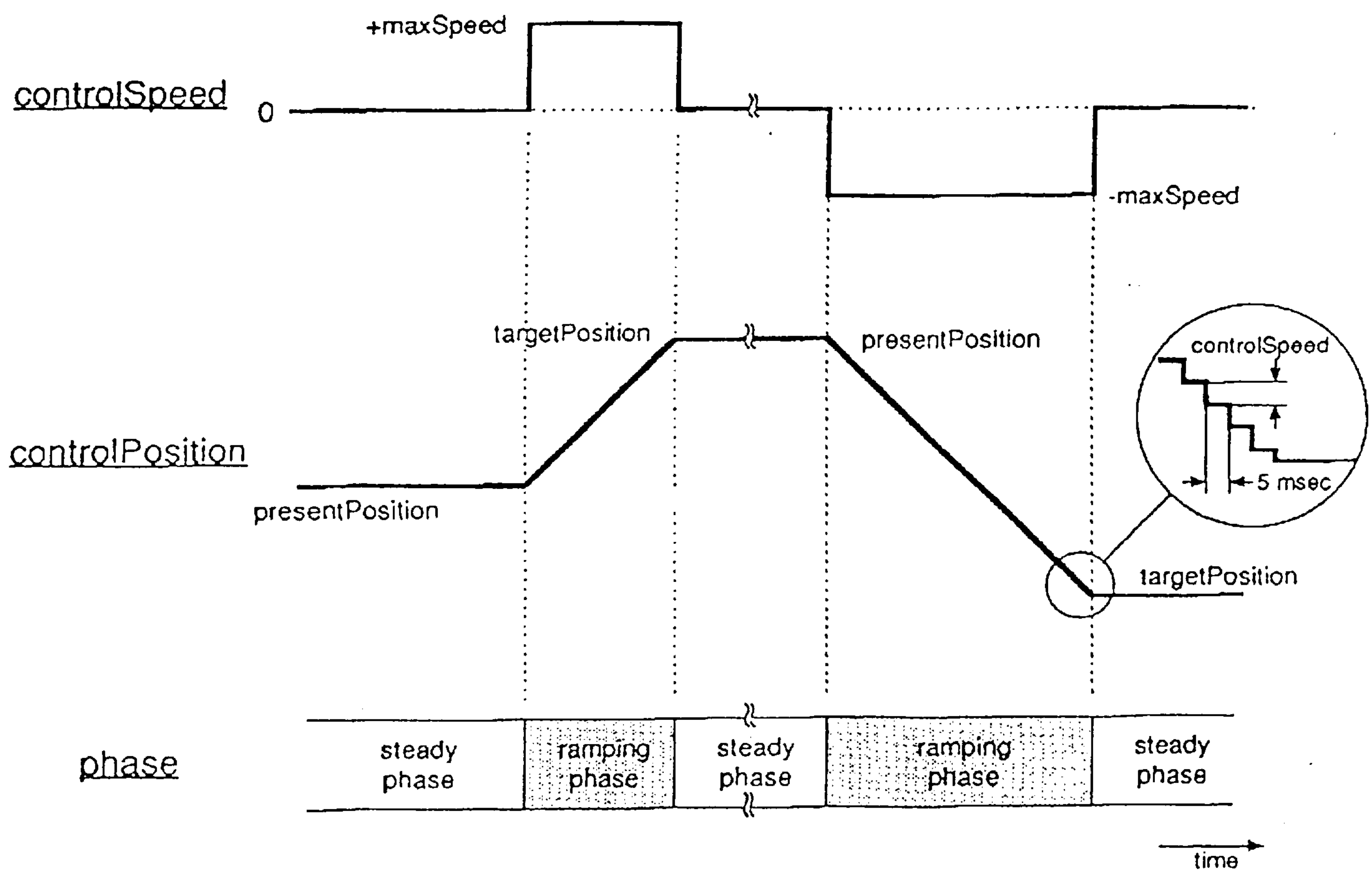

Figure 11 Trajectories of speed and position generated by Profile

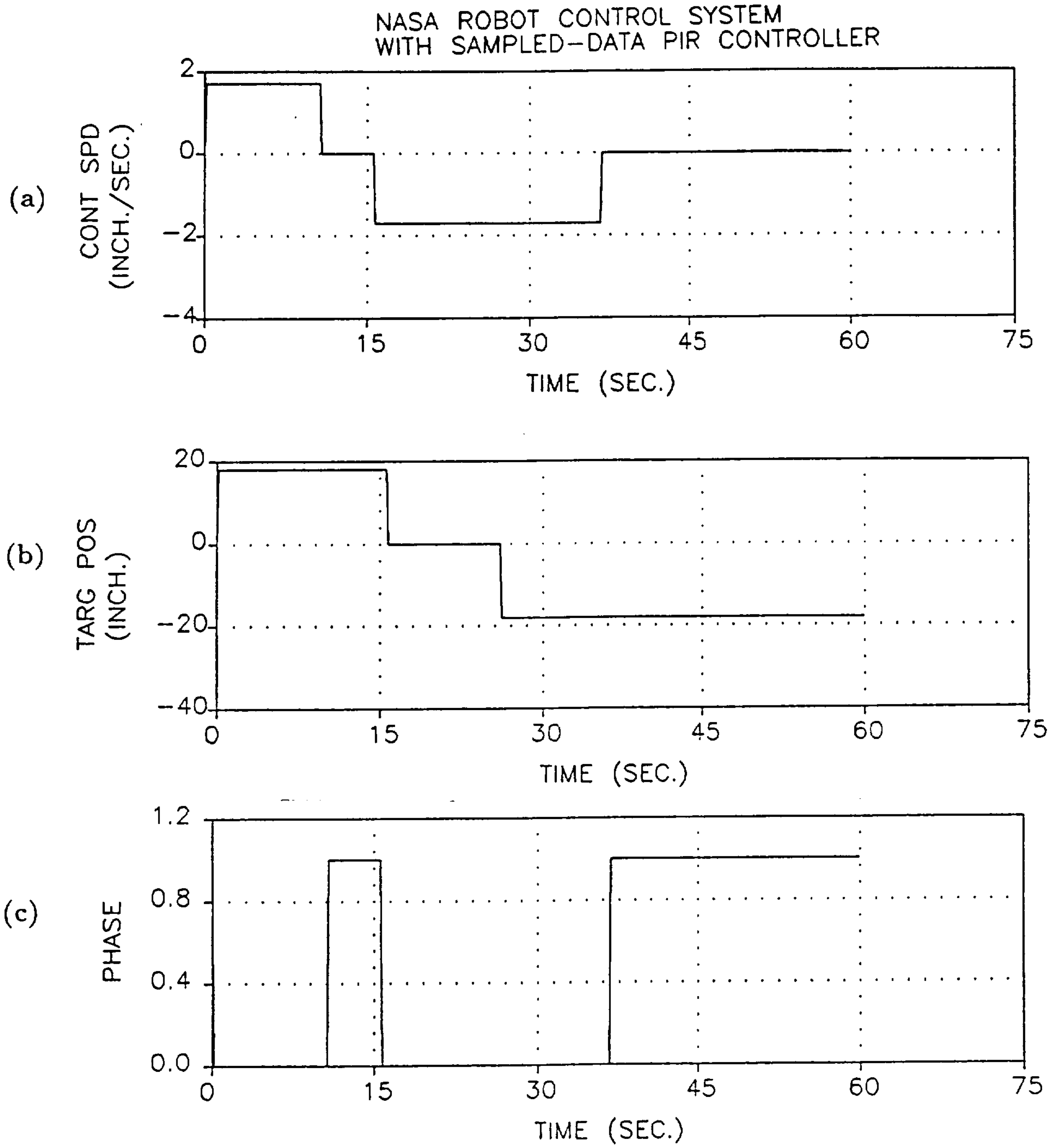

Figure 1.1.1: Simulation results of the elevation axis (study case 1): (a) time trajectory of control speed. (b) time trajectory of target position. (c) time trajectory of phase.

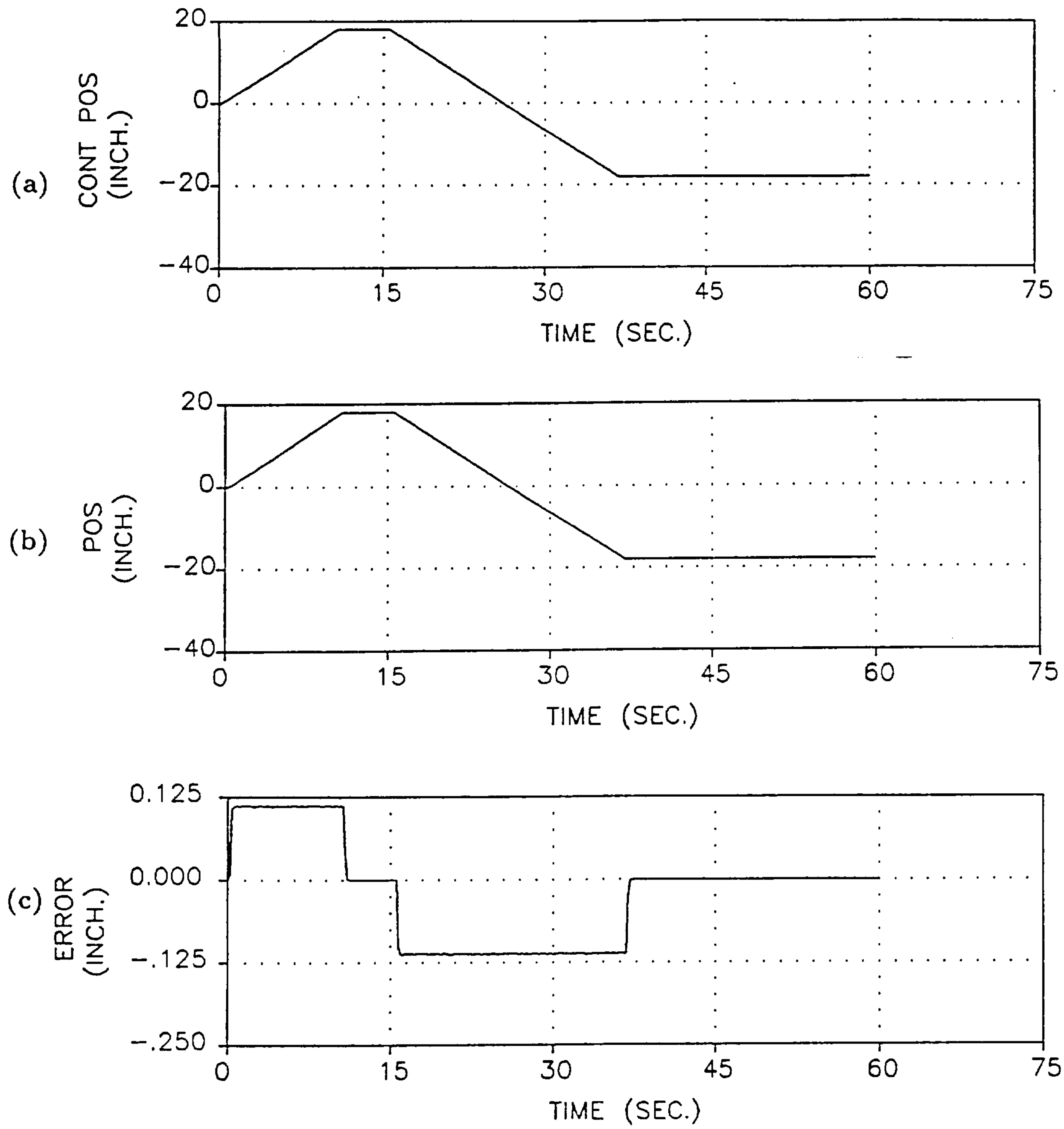

Figure 1.1.2: Simulation results of the elevation axis (study case 1): (a) time trajectory of control position. (b) time trajectory of output position. (c) time trajectory of tracking error.

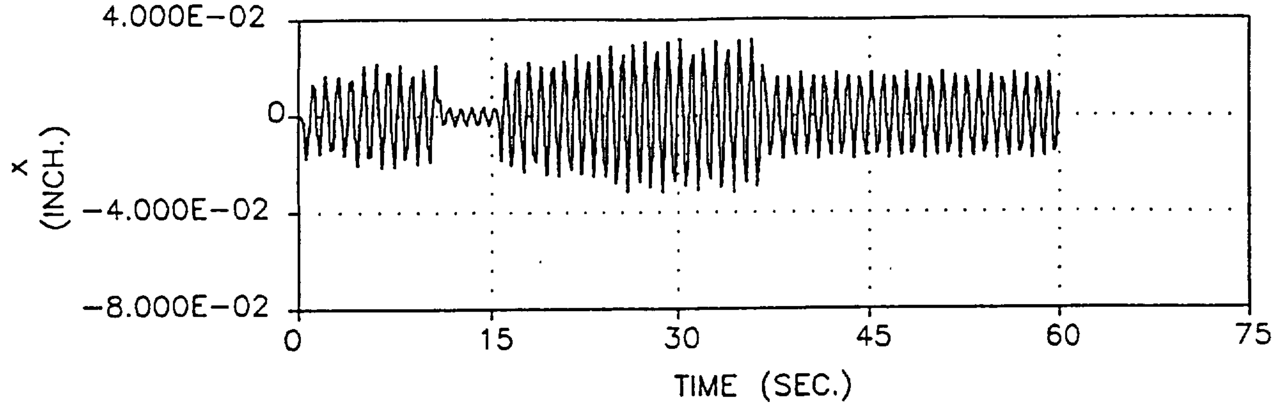

Figure 1.1.3: Simulation results of the elevation axis (study case 1): time trajectory of the displacement of the spring-mass model.

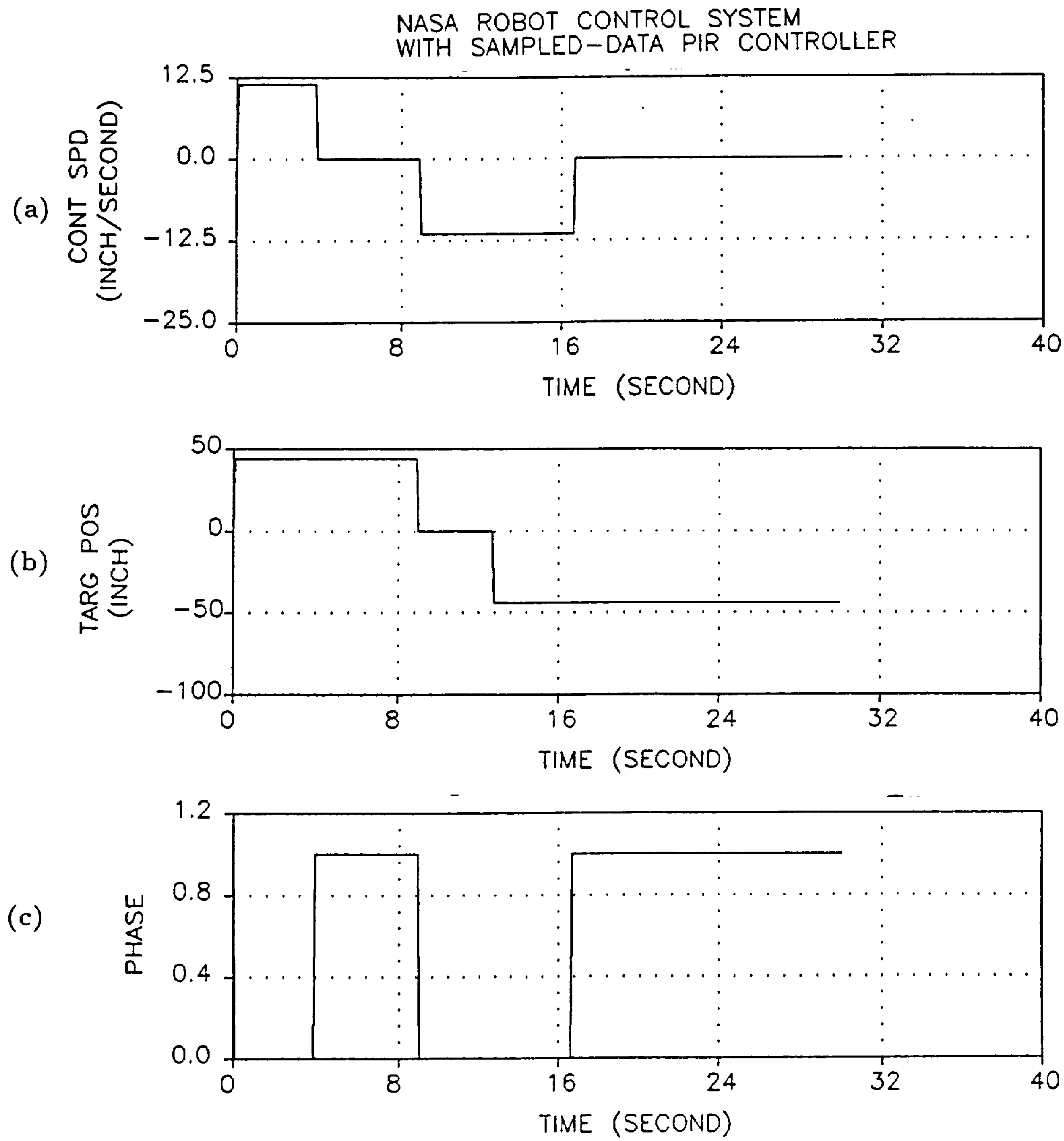

Figure 1.2.1: Simulation results of the azimuth axis (study case 1): (a) time trajectory of control speed. (b) time trajectory of target position. (c) time trajectory of phase.

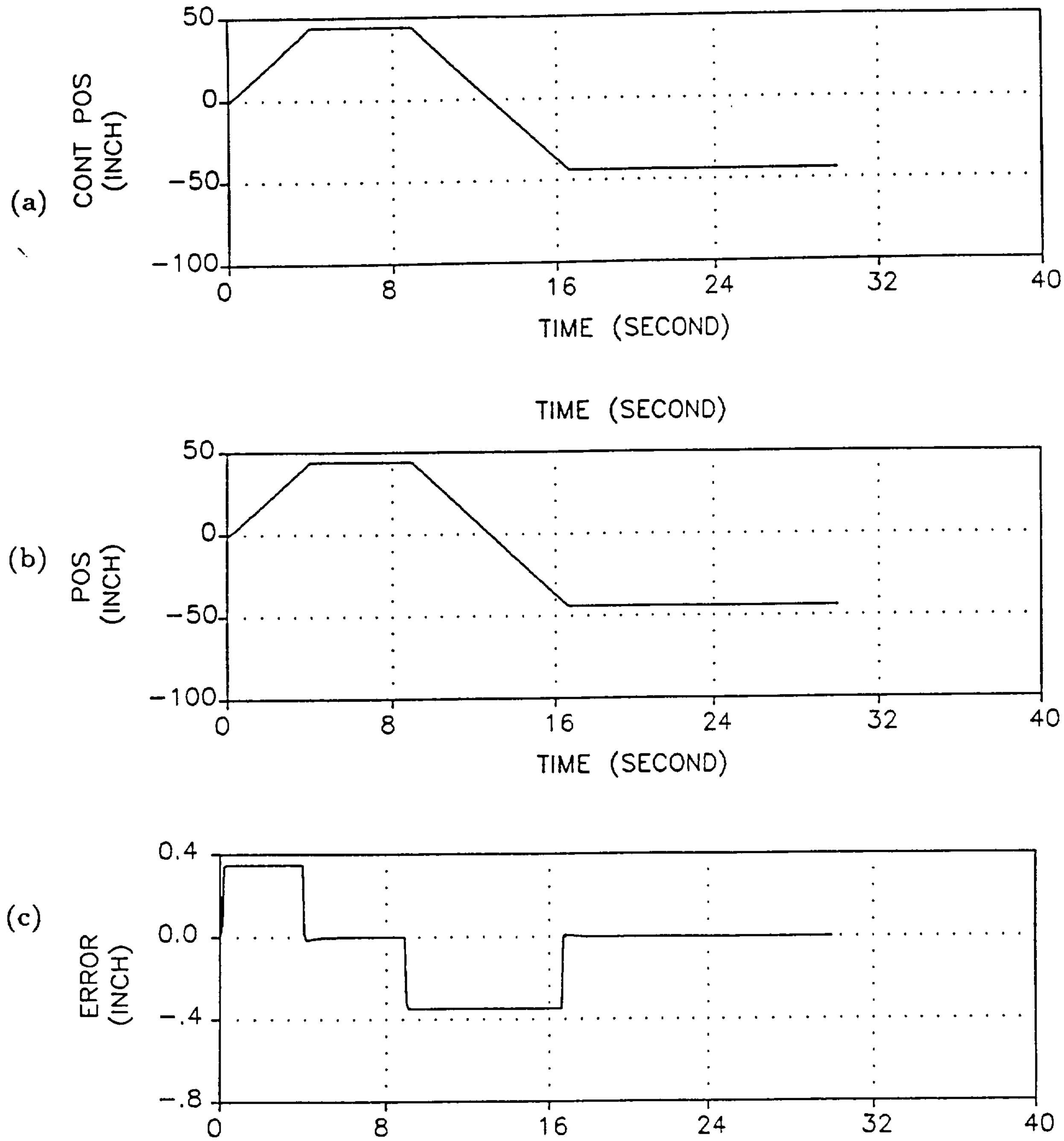

Figure 1.2.2: Simulation results of the azimuth axis (study case 1): (a) time trajectory of control position. (b) time trajectory of output position. (c) time trajectory of tracking error.

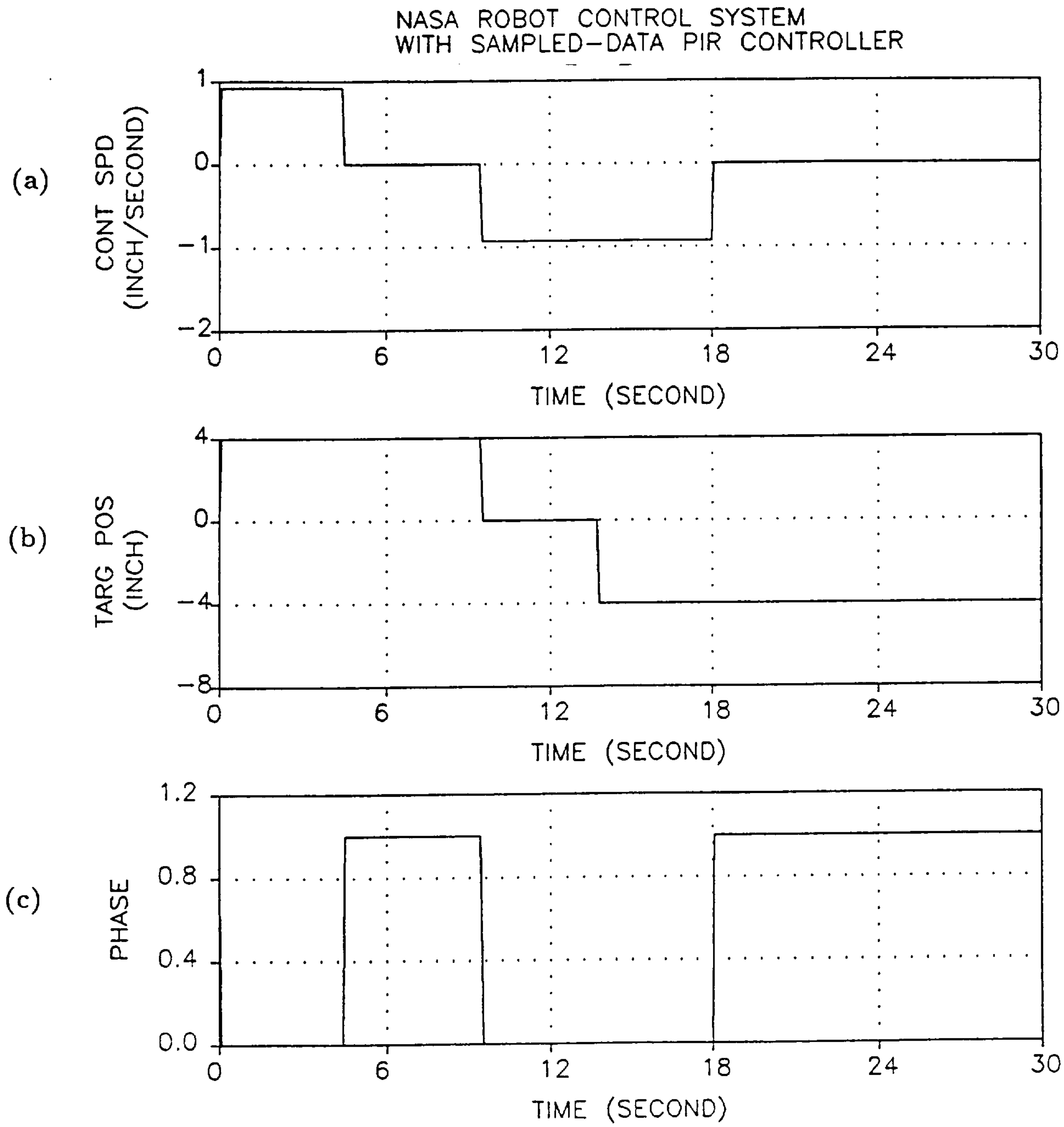

Figure 1.3.1: Simulation results of the radial axis (study case 1): (a) time trajectory of control speed. (b) time trajectory of target position. (c) time trajectory of phase.

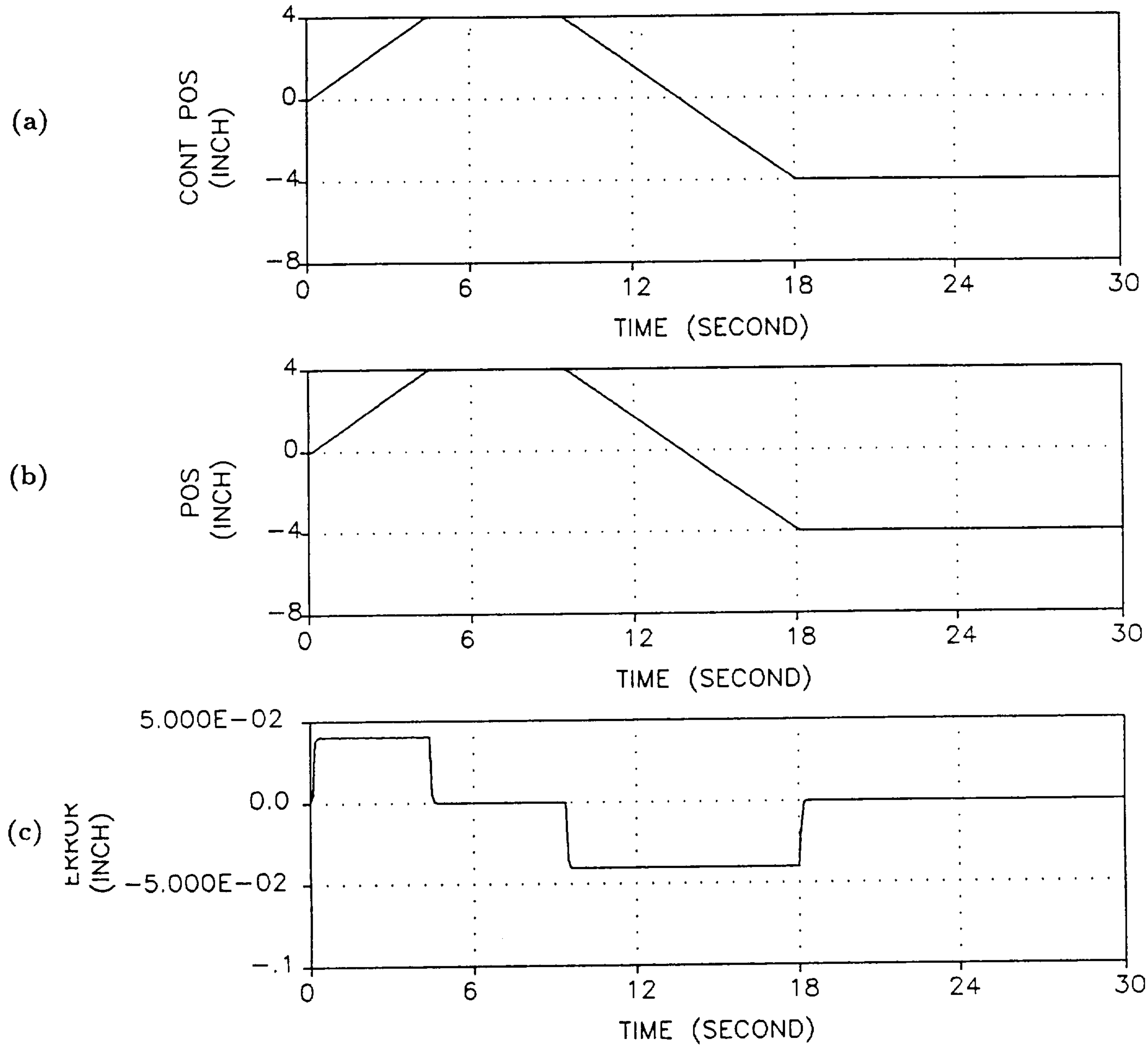

Figure 1.3.2: Simulation results of the radial axis (study case 1): (a) time trajectory of control position. (b) time trajectory of output position. (c) time trajectory of tracking error.

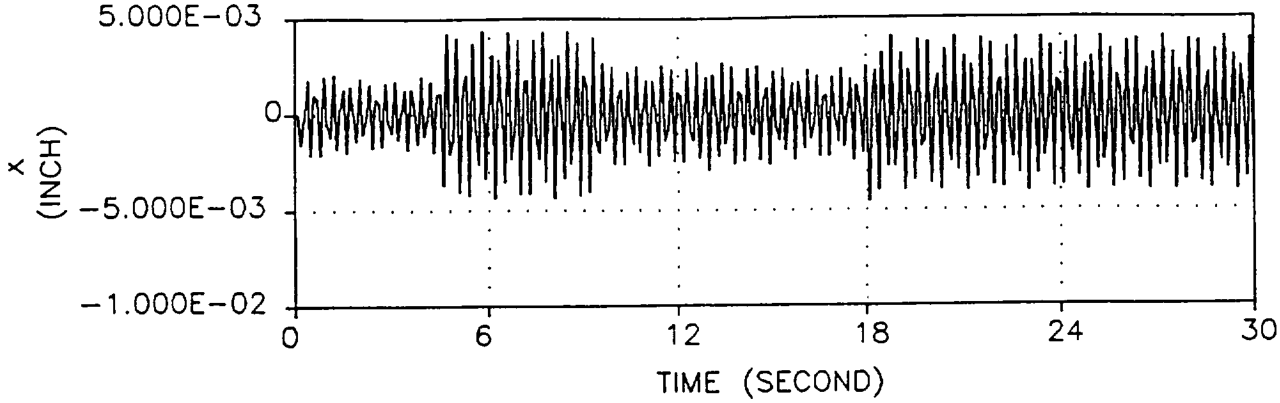

Figure 1.3.3: Simulation results of the radial axis (study case 1): time trajectory of the displacement of the spring-mass model.

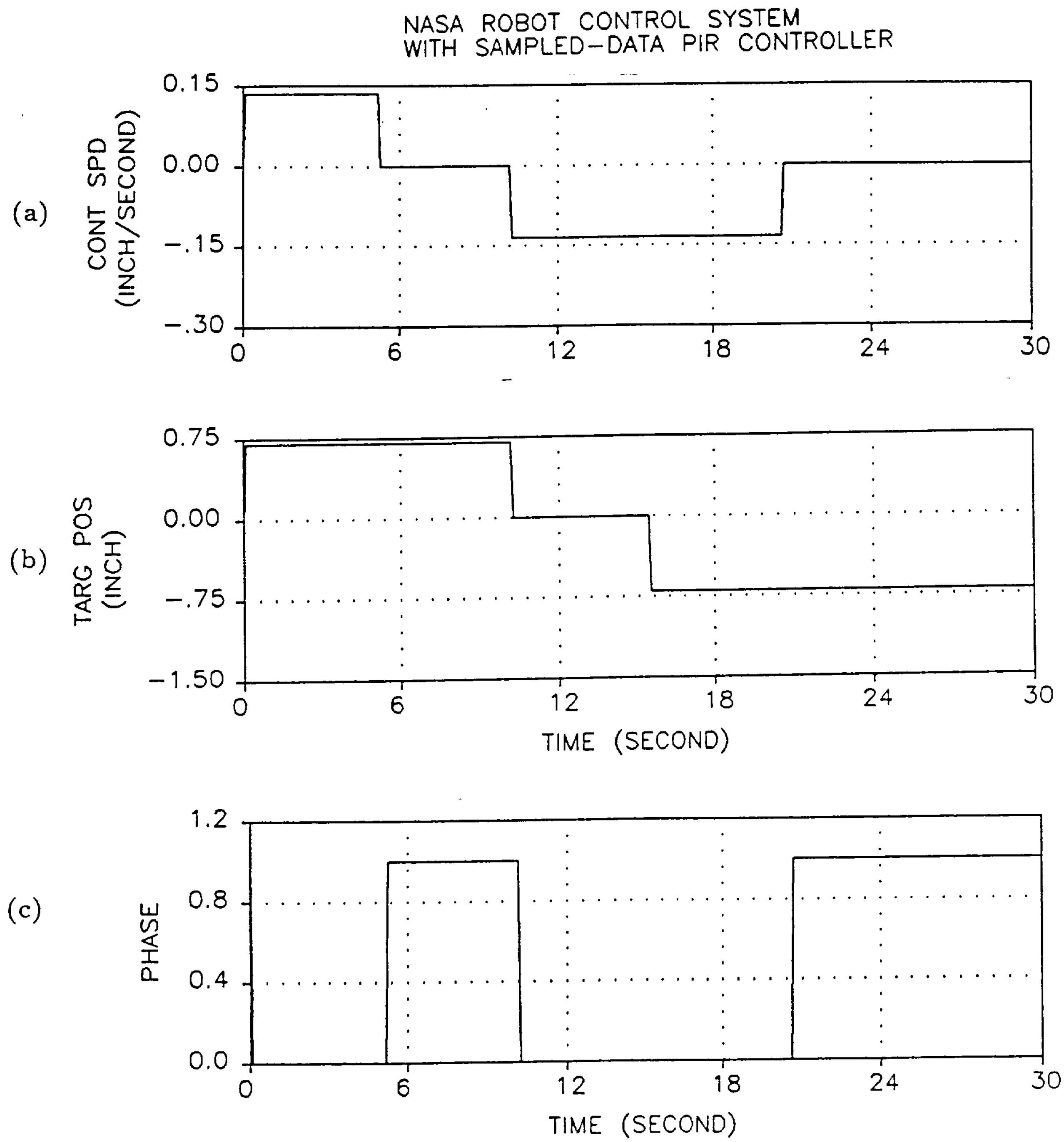

Figure 1.4.1: Simulation results of the gripper axis (study case 1): (a) time trajectory of control speed. (b) time trajectory of target position. (c) time trajectory of phase.

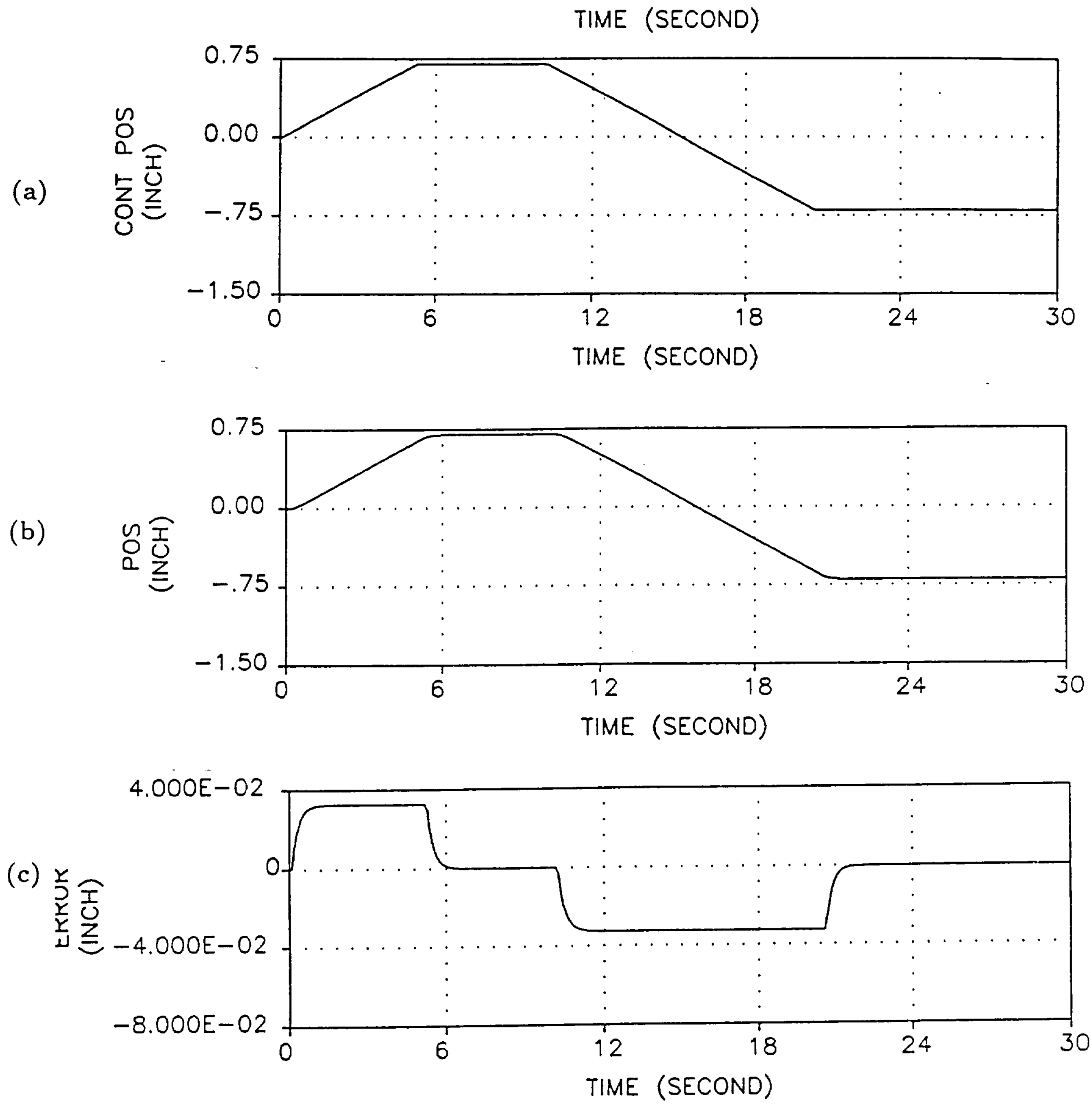

Figure 1.4.2: Simulation results of the gripper axis (study case 1): (a) time trajectory of control position. (b) time trajectory of output position. (c) time trajectory of tracking error.

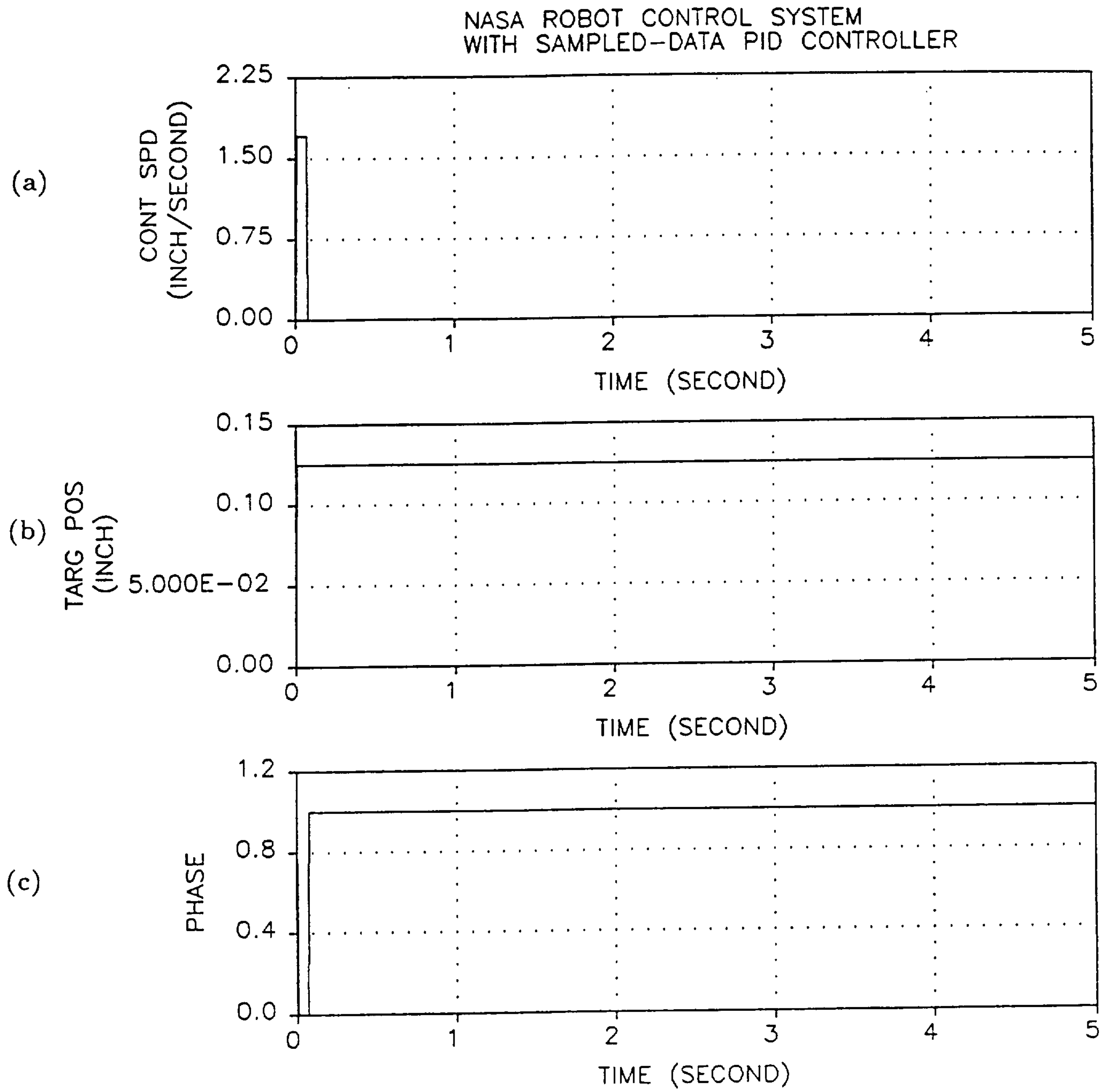

Figure 2.1: Simulation results of the elevation axis (study case 2): (a) time trajectory of control speed. (b) time trajectory of target position. (c) time trajectory of phase.

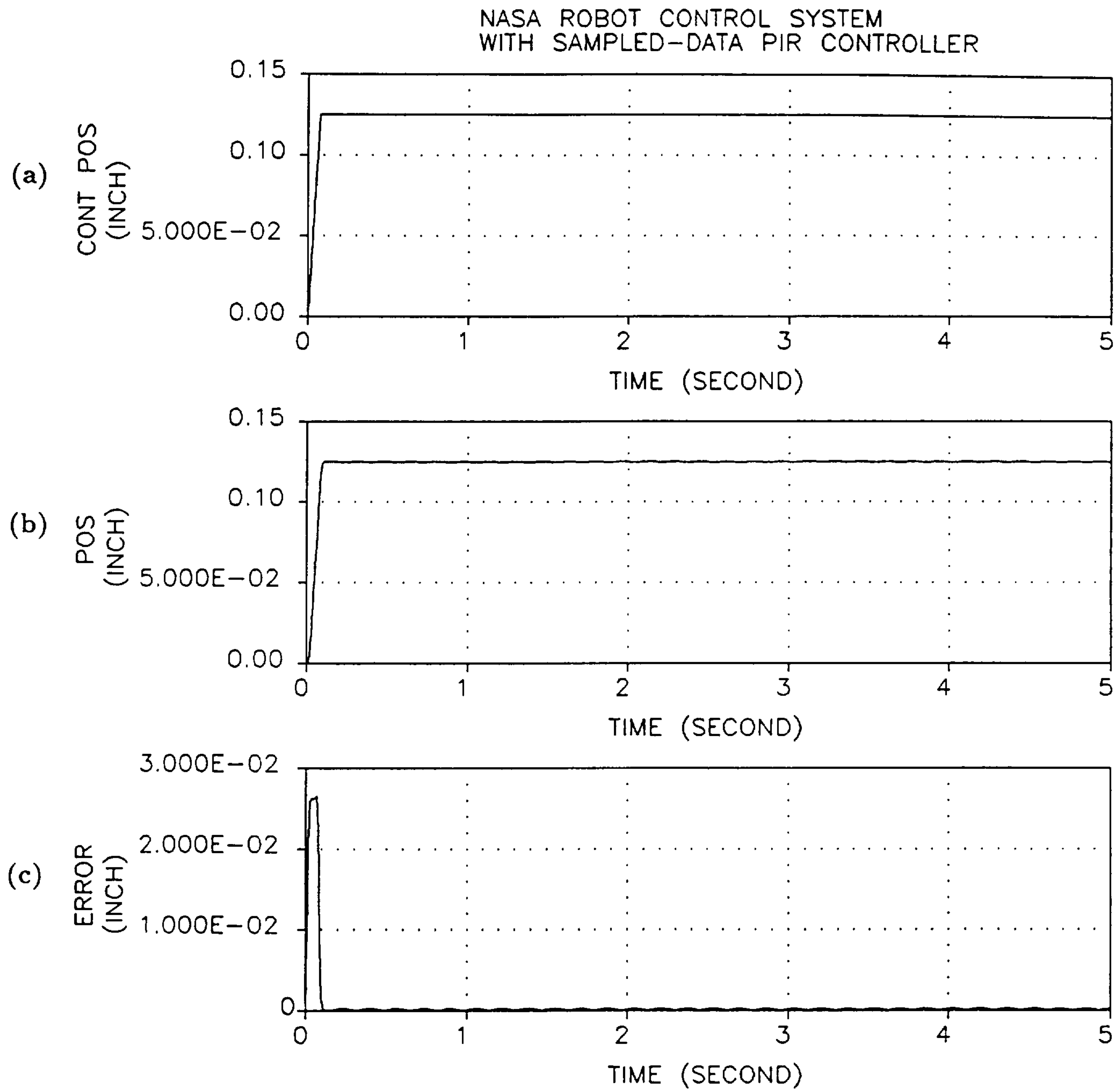

Figure 2.2: Simulation results of the elevation axis (study case 2): (a) time trajectory of control position. (b) time trajectory of output position. (c) time trajectory of tracking error.

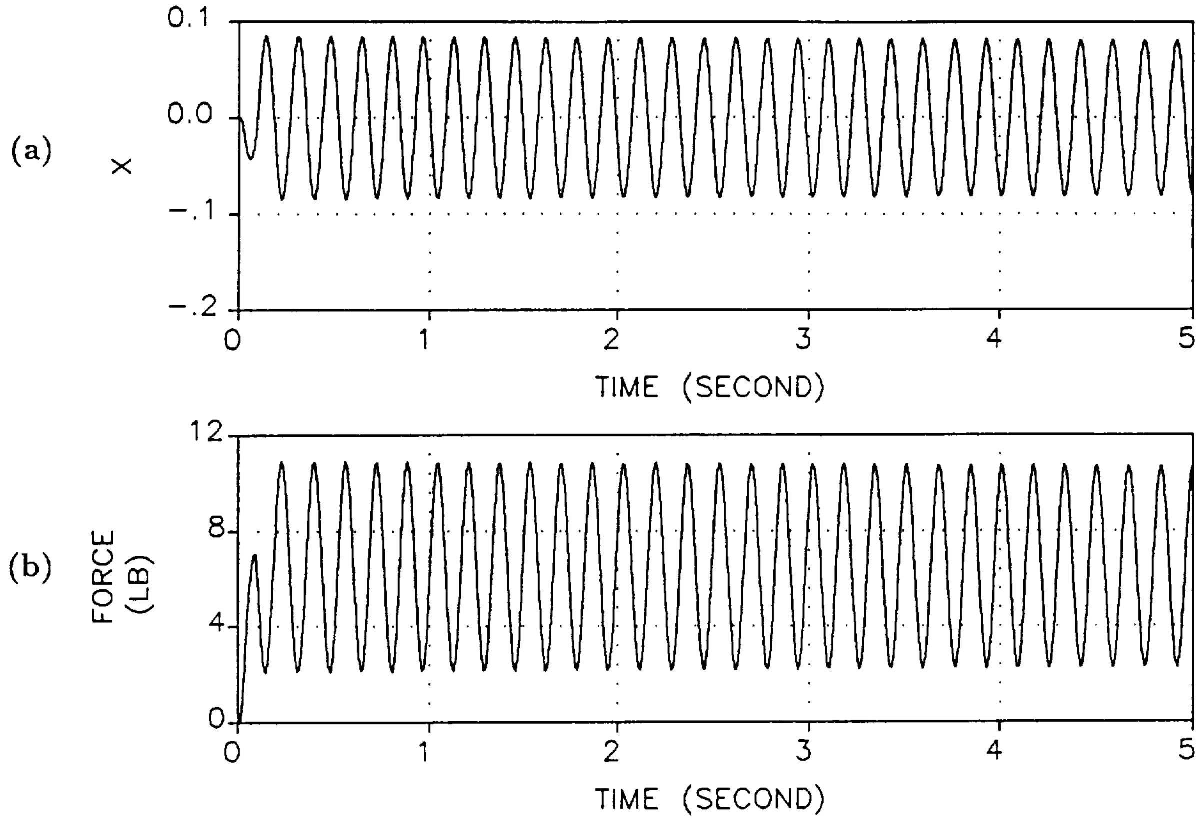

Figure 2.3: Simulation results of the elevation axis (study case 2) with $Max\_spd = 1.7087$ $(\frac{in}{sec})$: (a) time trajectory of displacement of the spring-mass model. (b) time trajectory of contact force.

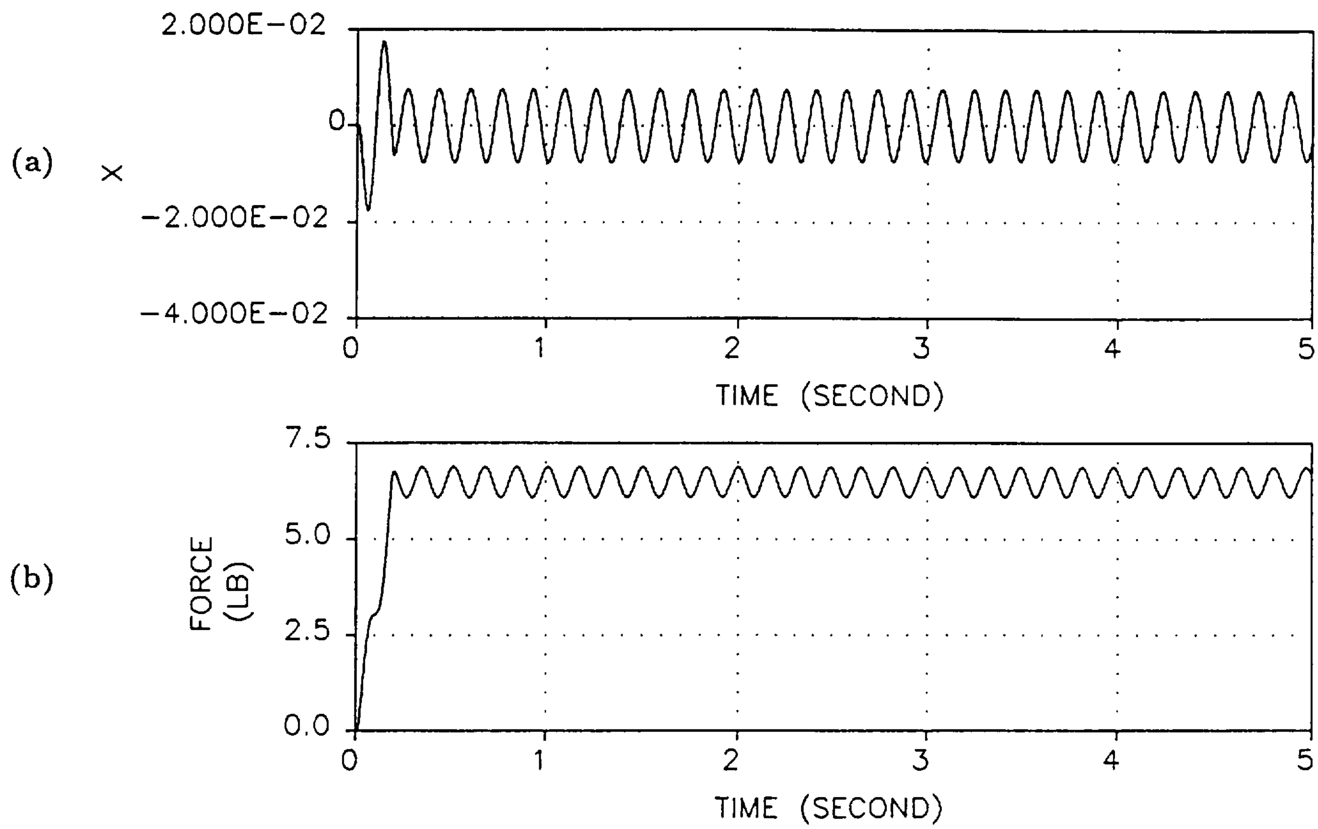

Figure 2.4: Simulation results of the elevation axis (study case 2) with Max_spd = 0.7087 ($\frac{in}{sec}$): (a) time trajectory of displacement of the spring-mass model. (b) time trajectory of contact force.

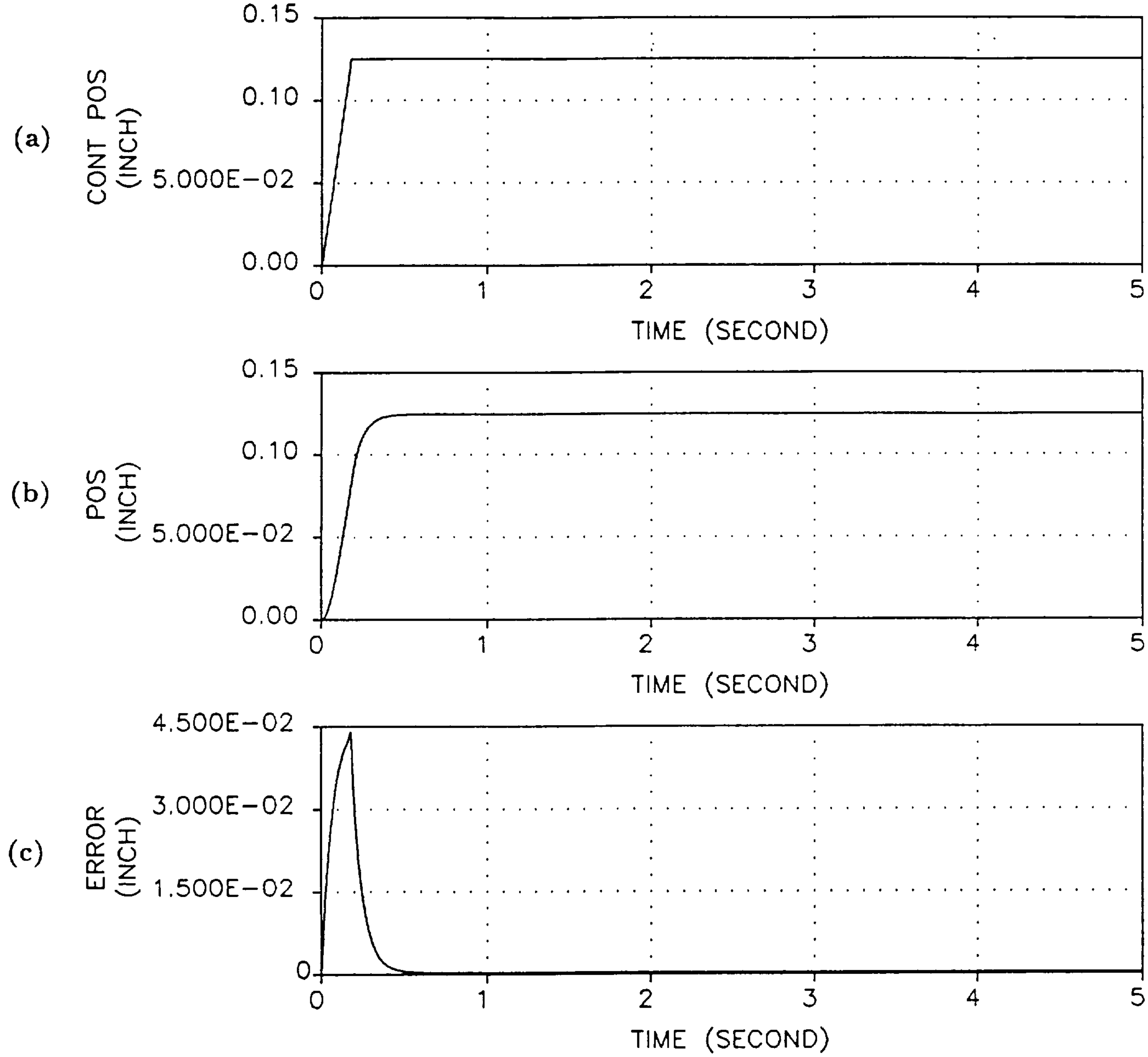

Figure 2.5: Simulation results of the elevation axis (study case 2) with $K_P = 440$, $K_I = 0.01$ and $K_R = 15$: (a) time trajectory of control position. (b) time trajectory of output position. (c) time trajectory of tracking error.

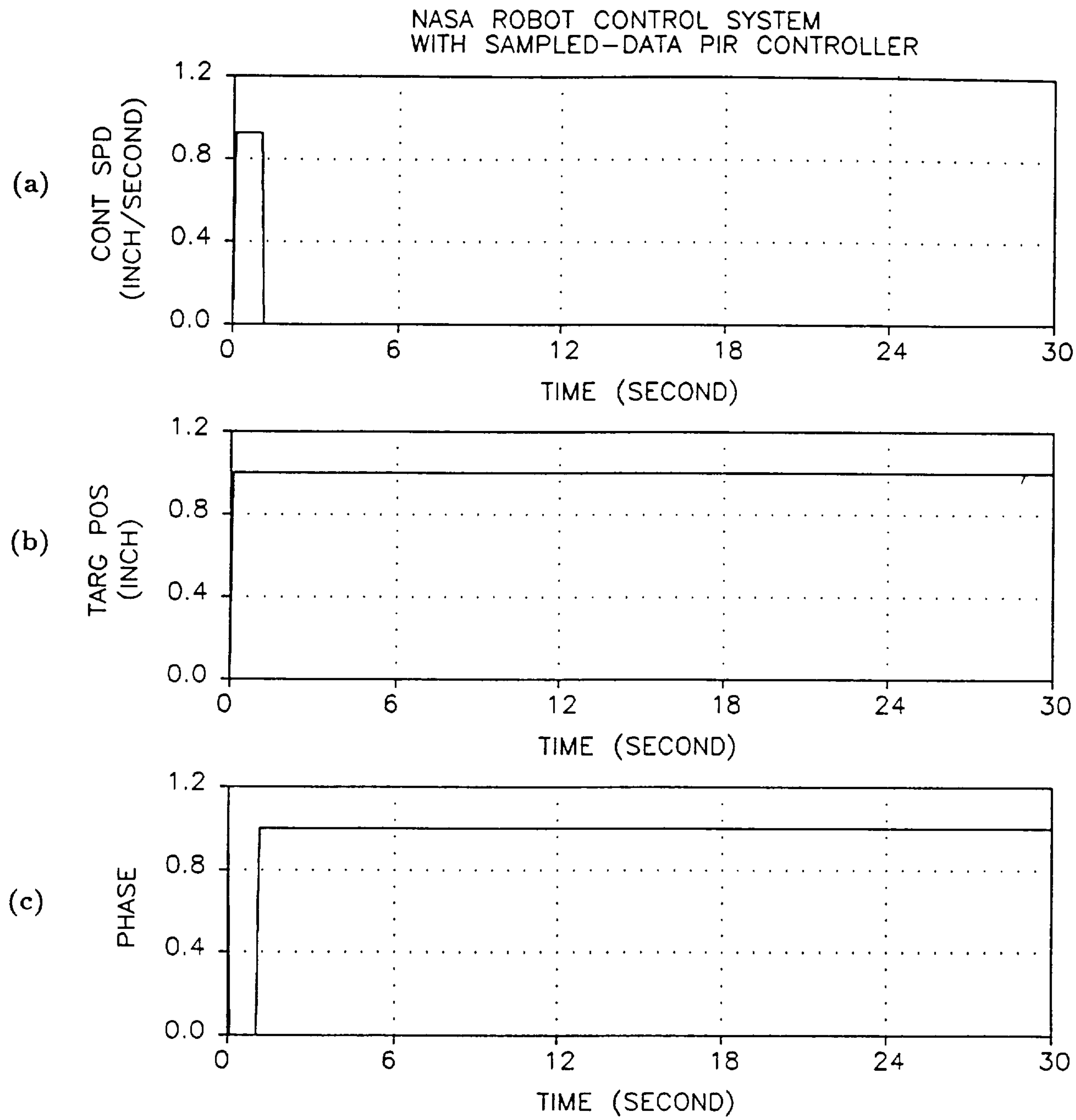

Figure 3.1: Simulation results of the radial axis (study case 3): (a) time trajectory of control speed. (b) time trajectory of target position. (c) time trajectory of phase.

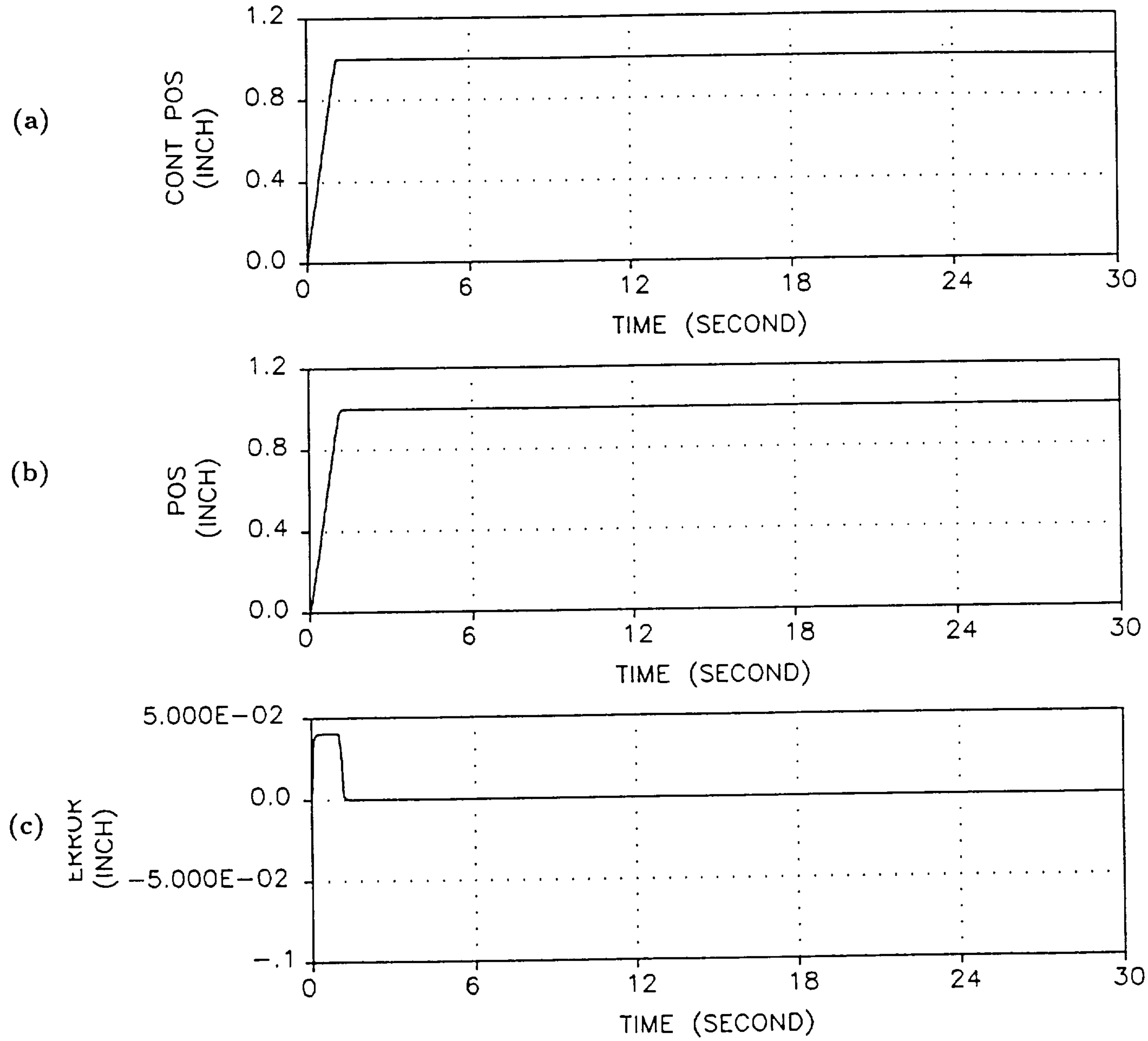

Figure 3.2: Simulation results of the radial axis (study case 3): (a) time trajectory of control position. (b) time trajectory of output position. (c) time trajectory of tracking error.

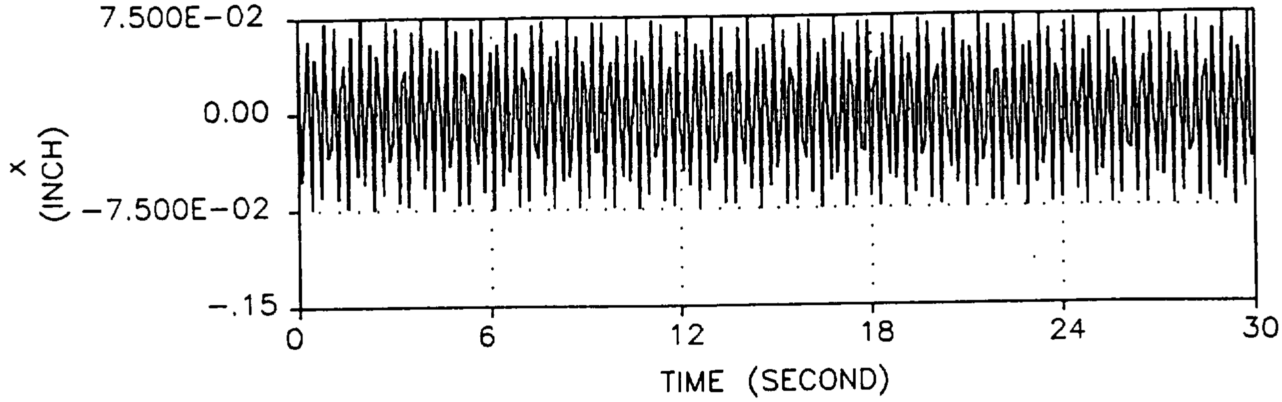

Figure 3.3: Simulation results of the radial axis (study case 3): time trajectory of the displacement of the spring-mass model.

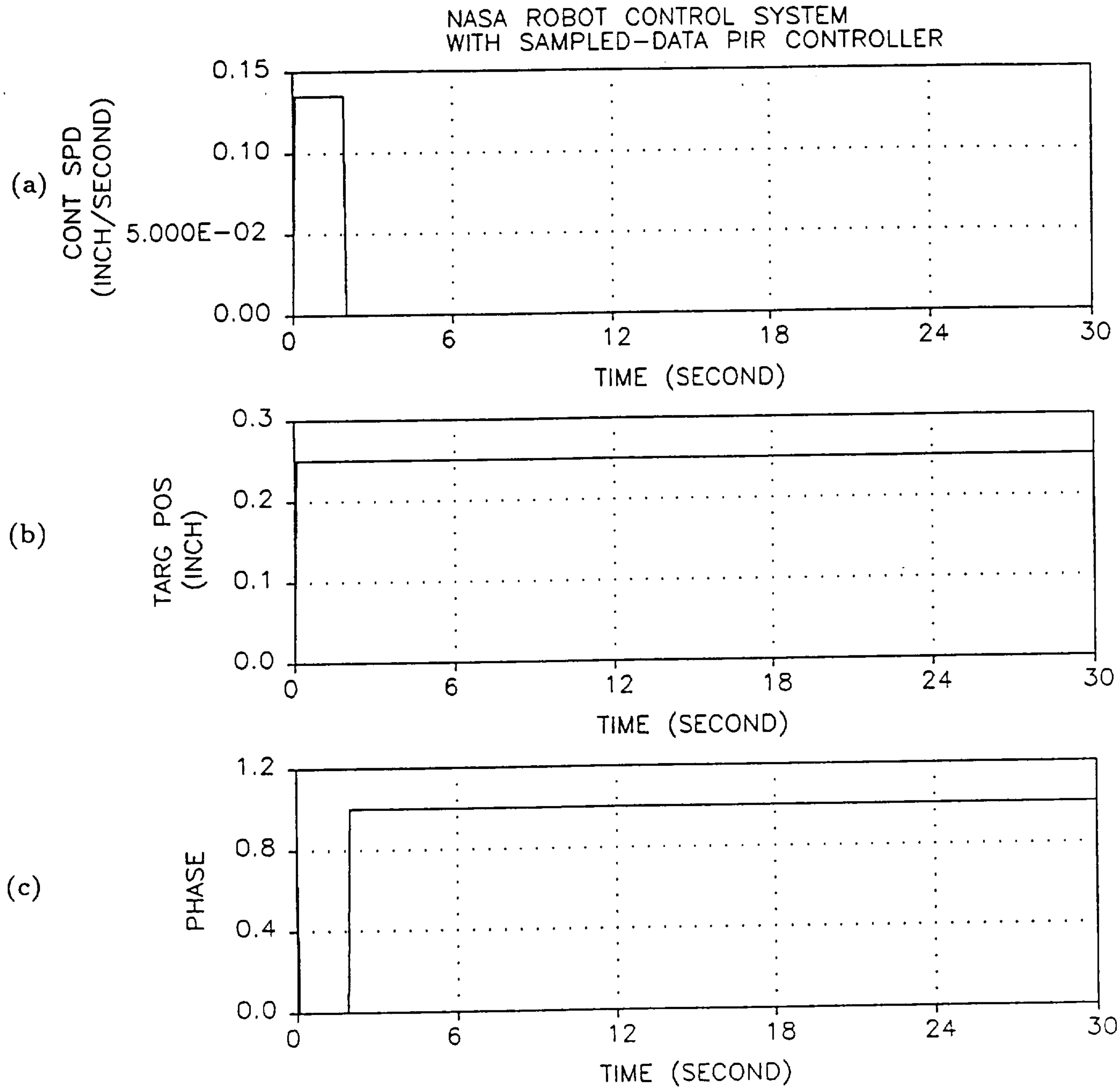

Figure 4.1: Simulation results of the gripper axis (study case 4): (a) time trajectory of control speed. (b) time trajectory of target position. (c) time trajectory of phase.

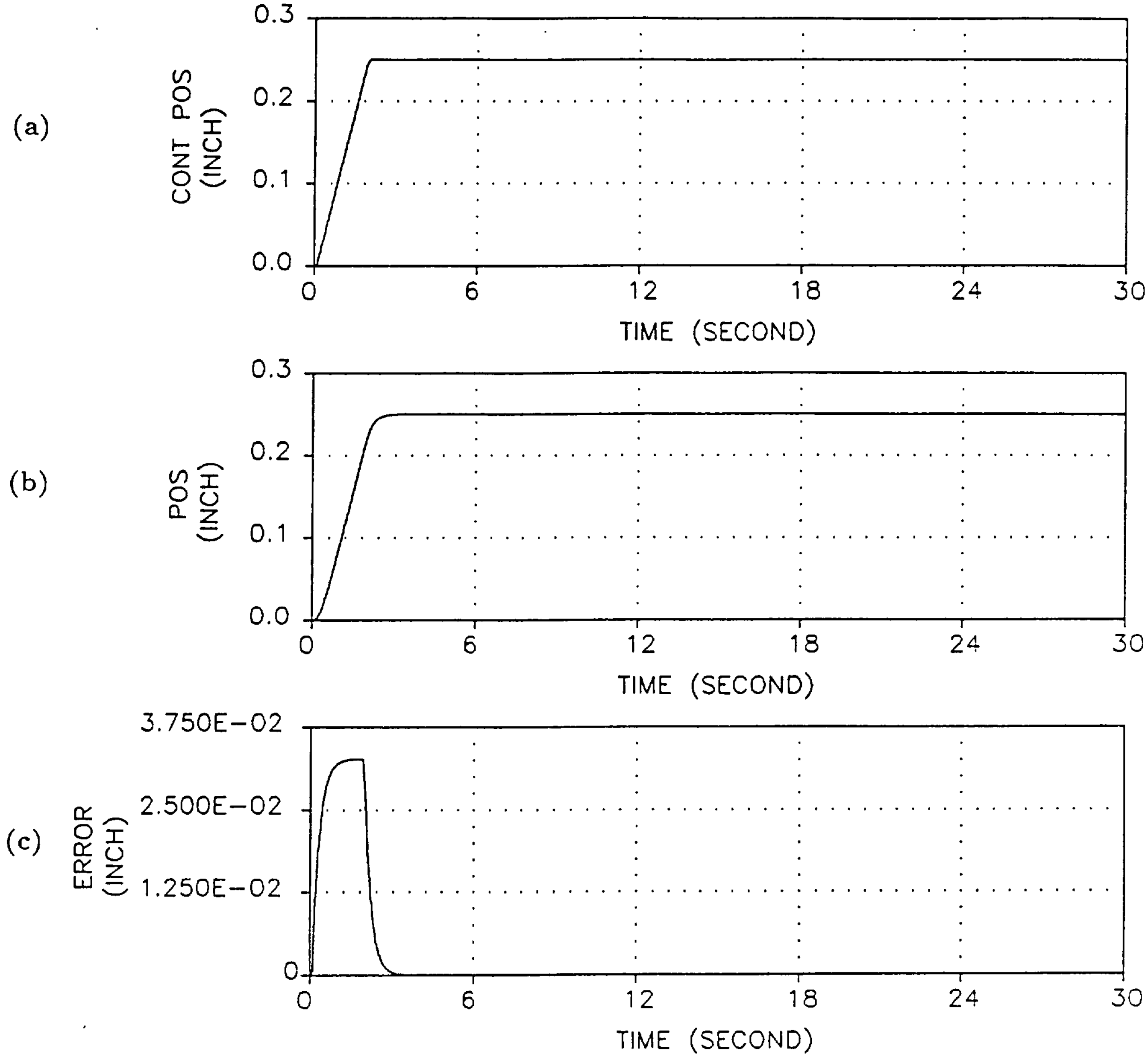

Figure 4.2: Simulation results of the gripper axis (study case 4): (a) time trajectory of control position. (b) time trajectory of output position. (c) time trajectory of tracking error.

(a)

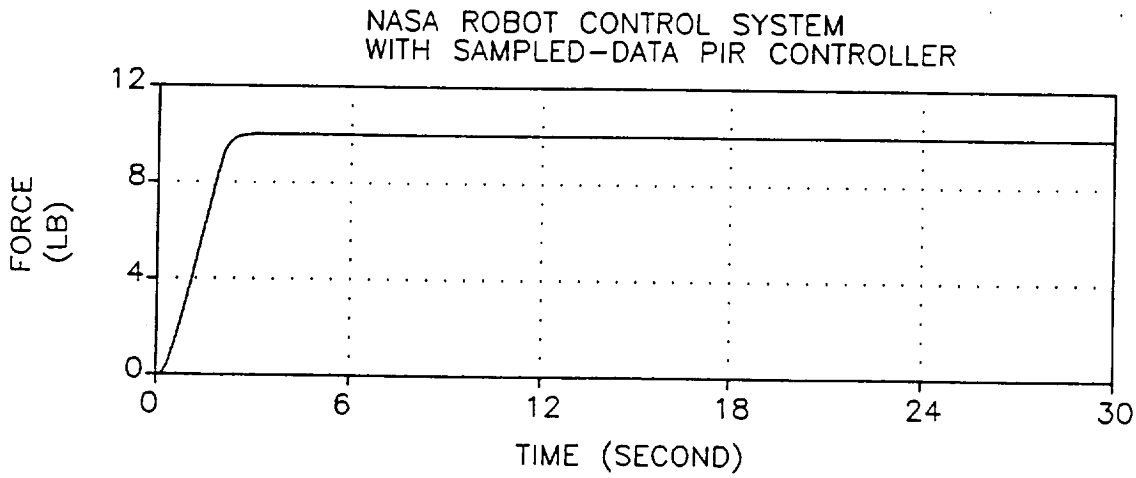

Figure 4.3: Simulation results of the gripper axis (study case 4): time trajectory of contact force.

```
*.....PROGRAM NAE.DAT (STUDY CASE 1: ELEVATION AXIS)
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER

INTGER INIT_SEQ

INITIAL
      DELS=TSAMP
      INIT_SEQ=0
DYNAMIC
*
*-----DIGITAL PID CONTROLLER
*
      TARG_P1=STEP(0.1)-STEP(15.6343)-STEP(26.1686)
      TARG_POS=18*TARG_P1
*
NOSORT
      TEST=SAMPLE(0.0,FINTIM,TSAMP)
      IF(TEST.EQ.0.0) GO TO 10
*-----SEQUENCER(INITIALIZE ON FIRST PASS ONLY)
      IF(INIT_SEQ.EQ.1) GO TO 20
      INIT_SEQ=1
      INTG_PRE=0.0
      LAST_POS=0.0
      CONT_POS=POS
      CONT_SPD=0.0
      PRES_POS=POS
      TARG_PRE=TARG_POS
   20 CONTINUE
*-----PROFILE
      IF(TARG_POS.EQ.TARG_PRE) GO TO 50
      IF(TARG_POS.GT.TARG_PRE) CONT_SPD=MAX_SPD
      IF(TARG_POS.LT.TARG_PRE) CONT_SPD=-MAX_SPD
      TARG_PRE=TARG_POS
      PHASE=0.0
   50 CONTINUE
      IF(ABS(CONT_POS-TARG_POS).LE.8.0E-3) THEN
                                           PHASE=1.0
                                           CONT_SPD=0.0
                                           CONT_POS=TARG_POS
                                           ENDIF
      PRES_POS=POS
      CONT_POS=CONT_POS+CONT_SPD*TSAMP
*-----ERROR
      ERROR=CONT_POS-PRES_POS
*-----INTEGRATE
      INTG=INTG_PRE+PHASE*ERROR*IFACTOR/ISCALE
      INTG_PRE=INTG
      INTG_LIM=PHASE*LIMIT(-ILIMIT,ILIMIT,INTG)
*-----TACH
      SPEED=(PRES_POS-LAST_POS)/TSAMP
      LAST_POS=PRES_POS
*-----PROPORTION
      PROP=ERROR*PFACTOR/PSCALE
*-----DERIVE
      DERIV=SPEED*DFACTOR/DSCALE
*     PID
      VOLTAGE=LIMIT(-MAX_VOLT,MAX_VOLT,PROP+INTG_LIM-DERIV)
   10 CONTINUE
SORT
```

```
      E2=VOLTAGE-KB*OMEGA
      C1=REALPL(0.0,L/R,(1/R)*E2)
      C1_LIM=LIMIT(-MAX_CURR,MAX_CURR,C1)
      TM=KT*C1_LIM
      C2=TM-TL
      OMEGA=REALPL(0.0,J/F,(1/F)*C2)
      THETA=INTGRL(0.0,OMEGA)
      POS=KF*THETA
      ACCEL=KF*(C2-F*OMEGA)/J
      XDOT=INTGRL(0.0,(-K*X)/M-ACCEL)
      X   =INTGRL(A,XDOT)
INCON A=0.0
CONST M=3.5742E-2
PARAM IFACTOR=0.01, ISCALE=1.0, DFACTOR=15, DSCALE=1.0,...
      PFACTOR=440.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=1.7087,...
      MAX_VOLT=28.0, TSAMP=0.005,KB=0.169, L=1.8E-3, R=2.5,...
      MAX_CURR=1.5, KT=24.0, TL=0, F=0.0162, J=5.0E-3, KF=.01253,...
      K=52

INTEG RKM
TIMER DELT=0.001, FINTIM=60.0, DELPR=1.0, DELGR=0.2
*PRINT POS,VELO,ACCEL,F,Y,ERROR
PRINT CONT_POS,POS,ERROR,X,ACCEL
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X
*PLOTS STRIP,MODEL=97,IOPORT=97
PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
GRAPH TIME, PHASE, TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
*GRAPH TIME, C1_LIM,VOLTAGE,INTG_LIM
GRAPH TIME, ACCEL,X
UNITS TIME(SEC.),TARG_POS(INCH.),CONT_POS(INCH.),...
      CONT_SPD(INCH./SEC.),POS(INCH.),ERROR(INCH.),...
      C1_LIM(AMPERE),VOLTAGE(VOLT), ACCEL(INCH./SEC.2),X(INCH.)
END
STOP
```

```
                    **** SYSL/PC SIMULATION DATA ****
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER
INCON A=0.0
CONST M=3.5742E-2
PARAM IFACTOR=0.01, ISCALE=1.0, DFACTOR=15, DSCALE=1.0,...
      PFACTOR=440.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=1.7087,...
      MAX_VOLT=28.0, TSAMP=0.005,KB=0.169, L=1.8E-3, R=2.5,...
      MAX_CURR=1.5, KT=24.0, TL=0, F=0.0162, J=5.0E-3, KF=.01253,...
      K=52
INTEG RKM
TIMER DELT=0.001, FINTIM=60.0, DELPR=1.0, DELGR=0.2
PRINT CONT_POS,POS,ERROR,X,ACCEL
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X
PLOTS STRIP,MODEL=97,IOPORT=97
GRAPH TIME, PHASE, TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
GRAPH TIME, ACCEL,X
UNITS TIME(SEC.),TARG_POS(INCH.),CONT_POS(INCH.),...
      CONT_SPD(INCH./SEC.),POS(INCH.),ERROR(INCH.),...
      C1_LIM(AMPERE),VOLTAGE(VOLT), ACCEL(INCH./SEC.2),X(INCH.)
END
```

**** SYSL/PC SIMULATOR OUTPUT -- 29-JUL-1994 13:19:28

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	CONT_POS	POS	ERROR	X	ACCEL
0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01
1.00000E+00	1.36696E+00	1.25549E+00	1.11465E-01	1.33757E-02	-3.46027E+01
2.00000E+00	3.07566E+00	2.96369E+00	1.11967E-01	1.69114E-02	6.19455E+01
3.00000E+00	4.78436E+00	4.67215E+00	1.12208E-01	1.63839E-02	4.44844E+01
4.00000E+00	6.49305E+00	6.38180E+00	1.11258E-01	1.50545E-02	7.64110E+00
5.00000E+00	8.20176E+00	8.08994E+00	1.11825E-01	9.02195E-03	-1.59357E+01
6.00000E+00	9.91056E+00	9.79855E+00	1.12006E-01	-2.46641E-04	1.81067E+01
7.00000E+00	1.16194E+01	1.15081E+01	1.11239E-01	-1.12468E-02	-3.02861E+01
8.00000E+00	1.33281E+01	1.32165E+01	1.11675E-01	-1.75701E-02	-3.77320E+01
9.00000E+00	1.50369E+01	1.49249E+01	1.12042E-01	-1.96515E-02	1.61976E+01
1.00000E+01	1.67456E+01	1.66339E+01	1.11762E-01	-1.87948E-02	-2.83323E+01
1.10000E+01	1.80000E+01	1.79984E+01	1.62697E-03	-3.15769E-03	7.78346E-01
1.20000E+01	1.80000E+01	1.80000E+01	-3.05176E-05	-3.93401E-03	-1.45201E-04
1.30000E+01	1.80000E+01	1.80000E+01	-3.05176E-05	-3.69270E-03	7.68221E-04
1.40000E+01	1.80000E+01	1.80000E+01	-3.05176E-05	-2.73678E-03	6.45469E-04
1.50000E+01	1.80000E+01	1.80000E+01	-3.05176E-05	-1.25117E-03	8.58413E-05
1.60000E+01	1.73678E+01	1.74801E+01	-1.12240E-01	4.41000E-03	-9.07679E+00
1.70000E+01	1.56592E+01	1.57705E+01	-1.11285E-01	1.51930E-02	8.23653E+00
1.80000E+01	1.39504E+01	1.40616E+01	-1.11196E-01	2.22679E-02	3.18305E+01
1.90000E+01	1.22416E+01	1.23540E+01	-1.12435E-01	2.03997E-02	-8.43822E+01
2.00000E+01	1.05328E+01	1.06436E+01	-1.10805E-01	1.99744E-02	9.55247E+01
2.10000E+01	8.82400E+00	8.93540E+00	-1.11394E-01	1.40737E-02	1.59137E+01
2.20000E+01	7.11526E+00	7.22700E+00	-1.11802E-01	3.03468E-03	7.18776E+00
2.30000E+01	5.40656E+00	5.51839E+00	-1.11893E-01	-6.15863E-03	2.03829E+01
2.40000E+01	3.69786E+00	3.80998E+00	-1.12120E-01	-1.87173E-02	-2.21141E+01
2.50000E+01	1.98916E+00	2.10131E+00	-1.12147E-01	-2.76400E-02	-1.67887E+01
2.60000E+01	2.80464E-01	3.91846E-01	-1.11382E-01	-3.13705E-02	4.14961E+00
2.70000E+01	-1.42676E+00	-1.31480E+00	-1.11967E-01	-2.73794E-02	-4.22805E+01
2.80000E+01	-3.13546E+00	-3.02346E+00	-1.11999E-01	-1.69647E-02	-2.99959E+01
2.90000E+01	-4.84416E+00	-4.73300E+00	-1.11158E-01	-4.55980E-03	9.54187E+01
3.00000E+01	-6.55286E+00	-6.44073E+00	-1.12129E-01	9.14982E-03	3.83727E+01
3.10000E+01	-8.26157E+00	-8.15042E+00	-1.11146E-01	2.07447E-02	3.05867E-01
3.20000E+01	-9.97036E+00	-9.85805E+00	-1.12312E-01	2.78882E-02	-2.06079E+01
3.30000E+01	-1.16792E+01	-1.15664E+01	-1.12797E-01	3.10860E-02	-1.18749E+01
3.40000E+01	-1.33880E+01	-1.32760E+01	-1.11966E-01	2.70168E-02	-2.36613E+01
3.50000E+01	-1.50967E+01	-1.49852E+01	-1.11506E-01	1.76498E-02	-3.84442E+01
3.60000E+01	-1.68054E+01	-1.66937E+01	-1.11704E-01	4.22108E-03	-1.35273E+01
3.70000E+01	-1.80000E+01	-1.79991E+01	-9.47952E-04	3.71713E-03	2.83082E-01
3.80000E+01	-1.80000E+01	-1.80000E+01	0.00000E-01	-4.00590E-03	-1.23957E-04
3.90000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-1.10815E-02	-1.03842E-04
4.00000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-1.60288E-02	-1.62505E-04
4.10000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-1.78769E-02	-3.50620E-04
4.20000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-1.62678E-02	-4.35038E-04
4.30000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-1.15164E-02	-1.88307E-04
4.40000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-4.52479E-03	-8.47714E-05
4.50000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	3.33674E-03	-5.62071E-04
4.60000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	1.05529E-02	-1.98359E-04
4.70000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	1.57350E-02	3.38042E-04
4.80000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	1.78559E-02	-6.70684E-05
4.90000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	1.65172E-02	2.51399E-04
5.00000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	1.19887E-02	2.73006E-04
5.10000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	5.14116E-03	3.60983E-05

**** SYSL/PC SIMULATOR OUTPUT -- 29-JUL-1994 13:19:28

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	CONT_POS	POS	ERROR	X	ACCEL
5.20000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-2.69898E-03	9.26530E-04
5.30000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-1.00142E-02	3.18392E-04
5.40000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-1.54029E-02	2.72027E-04
5.50000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-1.78067E-02	-4.81005E-04
5.60000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-1.67705E-02	-1.06436E-03
5.70000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-1.24993E-02	-9.01110E-05
5.80000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	-5.80251E-03	1.56188E-04
5.90000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	1.97253E-03	9.26474E-04
6.00000E+01	-1.80000E+01	-1.80000E+01	1.90735E-06	9.40953E-03	2.02031E-04

SIMULATION TIME = 79.418 SECONDS, UPDATE CALLS--355421, INTEGRATION STEPS-- 61

GRAPH PREPARATION TIME = 3.410 SECONDS

```
*.....PROGRAM NAA.DAT (STUDY CASE 1: AZIMUTH AXIS)
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER

INTGER INIT_SEQ

INITIAL
      DELS=TSAMP
      INIT_SEQ=0
DYNAMIC
*
*-----DIGITAL PID CONTROLLER
*
      TARG_P1=STEP(0.1)-STEP(8.9369)-STEP(12.7738)
      TARG_POS=44*TARG_P1
*
NOSORT
      TEST=SAMPLE(0.0,FINTIM,TSAMP)
      IF(TEST.EQ.0.0) GO TO 10
*-----SEQUENCER(INITIALIZE ON FIRST PASS ONLY)
      IF(INIT_SEQ.EQ.1) GO TO 20
      INIT_SEQ=1
      INTG_PRE=0.0
      LAST_POS=0.0
      CONT_POS=POS
      CONT_SPD=0.0
      PRES_POS=POS
      TARG_PRE=TARG_POS
   20 CONTINUE
*-----PROFILE
      IF(TARG_POS.EQ.TARG_PRE) GO TO 50
      IF(TARG_POS.GT.TARG_PRE) CONT_SPD=MAX_SPD
      IF(TARG_POS.LT.TARG_PRE) CONT_SPD=-MAX_SPD
      TARG_PRE=TARG_POS
      PHASE=0.0
   50 CONTINUE
      IF(ABS(CONT_POS-TARG_POS).LE.3.0E-2) THEN
                                           PHASE=1.0
                                           CONT_SPD=0.0
                                           CONT_POS=TARG_POS
                                           ENDIF
      PRES_POS=POS
      CONT_POS=CONT_POS+CONT_SPD*TSAMP
*-----ERROR
      ERROR=CONT_POS-PRES_POS
*-----INTEGRATE
      INTG=INTG_PRE+PHASE*ERROR*IFACTOR/ISCALE
      INTG_PRE=INTG
      INTG_LIM=PHASE*LIMIT(-ILIMIT,ILIMIT,INTG)
*-----TACH
      SPEED=(PRES_POS-LAST_POS)/TSAMP
      LAST_POS=PRES_POS
*-----PROPORTION
      PROP=ERROR*PFACTOR/PSCALE
*-----DERIVE
      DERIV=SPEED*DFACTOR/DSCALE
*     PID
      VOLTAGE=LIMIT(-MAX_VOLT,MAX_VOLT,PROP+INTG_LIM-DERIV)
   10 CONTINUE
SORT
```

```
        E2=VOLTAGE-KB*OMEGA
        C1=REALPL(0.0,L/R,(1/R)*E2)
        C1_LIM=LIMIT(-MAX_CURR,MAX_CURR,C1)
        TM=KT*C1_LIM
        C2=TM-TL
        OMEGA=REALPL(0.0,J/F,(1/F)*C2)
        THETA=INTGRL(0.0,OMEGA)
        POS=KF*THETA

  PARAM IFACTOR=10, ISCALE=1.0, DFACTOR=.01, DSCALE=1.0,...
        PFACTOR=150.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=11.4675,...
        MAX_VOLT=28.0, TSAMP=0.005,KB=0.0886, L=1.4E-3, R=2.9,...
        MAX_CURR=1.4, KT=12.5, TL=0, F=3.34E-3, J=1.2E-3, KF=0.04377

  INTEG RECT
  TIMER DELT=0.001, FINTIM=30.0, DELPR=1.0, DELGR=0.1
  PRINT ERROR,CONT_POS,POS,THETA,CONT_SPD
  *PRINT ERROR,POS,VOLTAGE,C1_LIM,INTG_LIM
  PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
         VOLTAGE, INTG_LIM,SPEED
  PLOTS STRIP,MODEL=97,IOPORT=97
  *PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
  GRAPH TIME, PHASE, TARG_POS, CONT_SPD
  GRAPH TIME, ERROR, POS, CONT_POS
  *GRAPH TIME,C1_LIM,VOLTAGE,SPEED
  *GRAPH TIME, POS
  UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
        CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),...
        C1_LIM(AMPERE),VOLTAGE(VOLT),SPEED(INCH/SECOND)
  END
  STOP
```

**** SYSL/PC SIMULATION DATA ****

```
TITLE NASA ROBOT CONTROL SYSTEM

TITLE WITH SAMPLED-DATA PIR CONTROLLER

PARAM IFACTOR=10, ISCALE=1.0, DFACTOR=.01, DSCALE=1.0,...

      PFACTOR=150.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=11.4675,...

      MAX_VOLT=28.0, TSAMP=0.005,KB=0.0886, L=1.4E-3, R=2.9,...

      MAX_CURR=1.4, KT=12.5, TL=0, F=3.34E-3, J=1.2E-3, KF=0.04377

INTEG RECT

TIMER DELT=0.001, FINTIM=30.0, DELPR=1.0, DELGR=0.1

PRINT ERROR,CONT_POS,POS,THETA,CONT_SPD

PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...

       VOLTAGE, INTG_LIM,SPEED

PLOTS STRIP,MODEL=97,IOPORT=97

GRAPH TIME, PHASE, TARG_POS, CONT_SPD

GRAPH TIME, ERROR, POS, CONT_POS

UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...

      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),...

      C1_LIM(AMPERE),VOLTAGE(VOLT),SPEED(INCH/SECOND)

END
```

**** SYSL/PC SIMULATOR OUTPUT -- 29-JUL-1994 18:00:10

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	ERROR	CONT_POS	POS	THETA	CONT_SPD
0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01
9.99991E-01	1.56870E-01	1.03781E+01	1.02327E+01	2.33783E+02	1.14675E+01
2.00004E+00	1.56861E-01	2.18455E+01	2.17001E+01	4.95777E+02	1.14675E+01
2.99996E+00	1.56871E-01	3.33129E+01	3.31675E+01	7.57769E+02	1.14675E+01
4.00089E+00	1.55640E-03	4.40000E+01	4.39985E+01	1.00522E+03	0.00000E-01
5.00082E+00	0.00000E-01	4.40000E+01	4.40000E+01	1.00525E+03	0.00000E-01
6.00075E+00	0.00000E-01	4.40000E+01	4.40000E+01	1.00525E+03	0.00000E-01
7.00068E+00	0.00000E-01	4.40000E+01	4.40000E+01	1.00525E+03	0.00000E-01
8.00060E+00	0.00000E-01	4.40000E+01	4.40000E+01	1.00525E+03	0.00000E-01
9.00001E+00	-1.63199E-01	4.32546E+01	4.34052E+01	9.91665E+02	-1.14675E+01
1.00004E+01	-1.56871E-01	3.17869E+01	3.19323E+01	7.29547E+02	-1.14675E+01
1.10008E+01	-1.56869E-01	2.03195E+01	2.04649E+01	4.67555E+02	-1.14675E+01
1.20002E+01	-1.56872E-01	8.85202E+00	8.99742E+00	2.05561E+02	-1.14675E+01
1.30006E+01	-1.56869E-01	-2.61547E+00	-2.47007E+00	-5.64329E+01	-1.14675E+01
1.40000E+01	-1.56875E-01	-1.40830E+01	-1.39376E+01	-3.18428E+02	-1.14675E+01
1.50004E+01	-1.56874E-01	-2.55504E+01	-2.54050E+01	-5.80420E+02	-1.14675E+01
1.60008E+01	-1.56863E-01	-3.70179E+01	-3.68725E+01	-8.42415E+02	-1.14675E+01
1.70003E+01	-1.64032E-04	-4.40000E+01	-4.39998E+01	-1.00525E+03	0.00000E-01
1.80007E+01	-7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
1.90002E+01	-7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
2.00006E+01	7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
2.10001E+01	7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
2.20005E+01	-7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
2.30000E+01	-7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
2.40004E+01	7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
2.50009E+01	7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
2.60003E+01	-7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
2.70008E+01	-7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
2.80002E+01	7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
2.90007E+01	-7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01
3.00001E+01	-7.62939E-06	-4.40000E+01	-4.40000E+01	-1.00525E+03	0.00000E-01

SIMULATION TIME = 4.502 SECONDS, UPDATE CALLS-- 30005, INTEGRATION STEPS-- 30
*** STRIP PLOTTING NOT AVAILABLE ***
*** STRIP PLOTTING NOT AVAILABLE ***

GRAPH PREPARATION TIME = 0.002 SECONDS

```
*.....PROGRAM NAR.DAT(STUDY CASE 1: RADIAL AXIS)
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER

INTGER INIT_SEQ

INITIAL
      DELS=TSAMP
      INIT_SEQ=0
DYNAMIC
*
*-----DIGITAL PID CONTROLLER
*
      TARG_P1=STEP(0.1)-STEP(9.4234)-STEP(13.7468)
      TARG_POS=4*TARG_P1
*
NOSORT
      TEST=SAMPLE(0.0,FINTIM,TSAMP)
      IF(TEST.EQ.0.0) GO TO 10
*-----SEQUENCER(INITIALIZE ON FIRST PASS ONLY)
      IF(INIT_SEQ.EQ.1) GO TO 20
      INIT_SEQ=1
      INTG_PRE=0.0
      LAST_POS=0.0
      CONT_POS=POS
      CONT_SPD=0.0
      PRES_POS=POS
      TARG_PRE=TARG_POS
   20 CONTINUE
*-----PROFILE
      IF(TARG_POS.EQ.TARG_PRE) GO TO 50
      IF(TARG_POS.GT.TARG_PRE) CONT_SPD=MAX_SPD
      IF(TARG_POS.LT.TARG_PRE) CONT_SPD=-MAX_SPD
      TARG_PRE=TARG_POS
      PHASE=0.0
   50 CONTINUE
      IF(ABS(CONT_POS-TARG_POS).LE.3.0E-3) THEN
                                     PHASE=1.0
                                     CONT_SPD=0.0
                                     CONT_POS=TARG_POS
                                     ENDIF
      PRES_POS=POS
      CONT_POS=CONT_POS+CONT_SPD*TSAMP
*-----ERROR
      ERROR=CONT_POS-PRES_POS
*-----INTEGRATE
      INTG=INTG_PRE+PHASE*ERROR*IFACTOR/ISCALE
      INTG_PRE=INTG
      INTG_LIM=PHASE*LIMIT(-ILIMIT,ILIMIT,INTG)
*-----TACH
      SPEED=(PRES_POS-LAST_POS)/TSAMP
      LAST_POS=PRES_POS
*-----PROPORTION
      PROP=ERROR*PFACTOR/PSCALE
*-----DERIVE
      DERIV=SPEED*DFACTOR/DSCALE
*     PID
      VOLTAGE=LIMIT(-MAX_VOLT,MAX_VOLT,PROP+INTG_LIM-DERIV)
   10 CONTINUE
SORT
```

```
        E2=VOLTAGE-KB*OMEGA
        C1=REALPL(0.0,L/R,(1/R)*E2)
        C1_LIM=LIMIT(-MAX_CURR,MAX_CURR,C1)
        TM=KT*C1_LIM
        C2=TM-TL
        OMEGA=REALPL(0.0,J/F,(1/F)*C2)
        THETA=INTGRL(0.0,OMEGA)
        POS=KF*THETA
        ACCEL=KF*(C2-F*OMEGA)/J
        XDOT=INTGRL(0.0,(-K*X)/M-ACCEL)
        X    =INTGRL(A,XDOT)
 INCON  A=0
 CONST  M=6.475E-3
 PARAM  IFACTOR=.01, ISCALE=1.0, DFACTOR=.01, DSCALE=1.0,...
        PFACTOR=600.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=0.9252,...
        MAX_VOLT=28, TSAMP=0.005,KB=0.016, L=0.55E-3, R=3.86,...
        MAX_CURR=0.45, KT=2.2, TL=0, F=1.1841E-4, J=2.67E-5,...
        KF=6.2659E-4 ,K=68

 INTEG RKM
 TIMER DELT=0.0001, FINTIM=30.0, DELPR=0.5, DELGR=0.1
 PRINT ERROR,POS,CONT_POS,ACCEL,X,
 *PRINT POS,ERROR,VOLTAGE,C1_LIM,INTG_LIM
 PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
         VOLTAGE, INTG_LIM,SPEED,ACCEL,X
 *PLOTS STRIP,MODEL=97,IOPORT=97
 PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
 *GRAPH TIME, PHASE, TARG_POS, CONT_SPD
 GRAPH TIME, ERROR, POS, CONT_POS
 *GRAPH TIME,C1_LIM,VOLTAGE,INTG_LIM
 GRAPH TIME, ACCEL,X
 UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
       CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),...
       C1_LIM(AMPERE),VOLTAGE(VOLT),SPEED(INCH/SECOND),...
       ACCEL(INCH/SECOND2),X(INCH)

 END
 STOP
```

```
**** SYSL/PC SIMULATION DATA ****
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER
INCON A=0
CONST M=6.475E-3
PARAM IFACTOR=.01, ISCALE=1.0, DFACTOR=.01, DSCALE=1.0,...
      PFACTOR=600.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=0.9252,...
      MAX_VOLT=28, TSAMP=0.005,KB=0.016, L=0.55E-3, R=3.86,...
      MAX_CURR=0.45, KT=2.2, TL=0, F=1.1841E-4, J=2.67E-5,...
      KF=6.2659E-4 ,K=68
INTEG RKM
TIMER DELT=0.0001, FINTIM=30.0, DELPR=0.5, DELGR=0.1
PRINT ERROR,POS,CONT_POS,ACCEL,X,
*** THE SYMBOL          HAS NOT BEEN DEFINED. IT HAS BEEN IGNORED ***
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X
PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
GRAPH TIME, ERROR, POS, CONT_POS
GRAPH TIME, ACCEL,X
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),...
      C1_LIM(AMPERE),VOLTAGE(VOLT),SPEED(INCH/SECOND),...
      ACCEL(INCH/SECOND2),X(INCH)
END
```

**** SYSL/PC SIMULATOR OUTPUT -- 02-AUG-1994 12:07:57

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	ERROR	POS	CONT_POS	ACCEL	X
0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01
5.00000E-01	4.00558E-02	3.34650E-01	3.74706E-01	-6.49933E-01	-2.09730E-03
1.00000E+00	4.01851E-02	7.97120E-01	8.37305E-01	-2.69980E-01	-5.50896E-04
1.50000E+00	4.01907E-02	1.25972E+00	1.29991E+00	-8.01620E-03	1.28581E-03
2.00000E+00	4.01616E-02	1.72235E+00	1.76251E+00	-3.56294E-01	1.86592E-03
2.50000E+00	4.00588E-02	2.18505E+00	2.22511E+00	-1.93856E-01	8.00683E-04
3.00000E+00	4.01463E-02	2.64757E+00	2.68772E+00	-5.24935E-02	-9.79816E-04
3.50000E+00	4.01537E-02	3.11017E+00	3.15032E+00	1.76488E-02	-1.84002E-03
4.00000E+00	4.00774E-02	3.57285E+00	3.61292E+00	-1.52705E-01	-1.14038E-03
4.50000E+00	4.48704E-03	3.99551E+00	4.00000E+00	-1.61800E+00	1.08213E-03
5.00000E+00	3.33786E-06	4.00000E+00	4.00000E+00	1.19590E-04	4.01053E-03
5.50000E+00	3.33786E-06	4.00000E+00	4.00000E+00	-3.54423E-05	3.71531E-03
6.00000E+00	3.33786E-06	4.00000E+00	4.00000E+00	5.72048E-05	1.69073E-04
6.50000E+00	1.66893E-06	4.00000E+00	4.00000E+00	-6.82492E-06	-3.52677E-03
7.00000E+00	1.19209E-06	4.00000E+00	4.00000E+00	-1.22653E-04	-4.13297E-03
7.50000E+00	1.19209E-06	4.00000E+00	4.00000E+00	1.54336E-04	-1.12116E-03
8.00000E+00	1.19209E-06	4.00000E+00	4.00000E+00	3.38309E-04	2.87426E-03
8.50000E+00	1.19209E-06	4.00000E+00	4.00000E+00	-2.59182E-04	4.35087E-03
9.00000E+00	1.19209E-06	4.00000E+00	4.00000E+00	-1.27415E-04	2.01757E-03
9.50000E+00	-3.54399E-02	3.96142E+00	3.92598E+00	-1.21953E+00	-1.99456E-03
1.00000E+01	-4.00884E-02	3.50347E+00	3.46338E+00	-1.15171E-01	-2.56043E-03
1.05000E+01	-4.00803E-02	3.04086E+00	3.00078E+00	1.05975E-01	-4.36967E-04
1.10000E+01	-4.01096E-02	2.57828E+00	2.53817E+00	4.58520E-01	1.75447E-03
1.15000E+01	-4.01289E-02	2.11570E+00	2.07557E+00	-4.20062E-01	2.53639E-03
1.20000E+01	-4.00759E-02	1.65304E+00	1.61297E+00	-1.15536E-02	1.12383E-03
1.25000E+01	-4.01716E-02	1.19053E+00	1.15036E+00	-4.55459E-01	-1.35514E-03
1.30000E+01	-4.01485E-02	7.27911E-01	6.87762E-01	-5.43829E-01	-2.90283E-03
1.35000E+01	-4.00590E-02	2.65222E-01	2.25163E-01	-7.53527E-02	-1.54853E-03
1.40000E+01	-4.00518E-02	-1.97385E-01	-2.37437E-01	-4.73887E-01	1.00455E-03
1.45000E+01	-4.01194E-02	-6.59917E-01	-7.00036E-01	-3.34806E-01	2.51434E-03
1.50000E+01	-4.01771E-02	-1.12246E+00	-1.16264E+00	5.09867E-01	2.20705E-03
1.55000E+01	-4.01044E-02	-1.58514E+00	-1.62524E+00	1.62990E-01	2.08076E-04
1.60000E+01	-4.00757E-02	-2.04777E+00	-2.08784E+00	-1.76709E-01	-1.79265E-03
1.65000E+01	-4.00965E-02	-2.51035E+00	-2.55045E+00	-3.94858E-01	-2.21721E-03
1.70000E+01	-4.01406E-02	-2.97291E+00	-3.01305E+00	3.73320E-02	-3.08069E-04
1.75000E+01	-4.01160E-02	-3.43554E+00	-3.47565E+00	4.39837E-01	1.79073E-03
1.80000E+01	-4.00414E-02	-3.89822E+00	-3.93826E+00	-2.42690E-02	2.47652E-03
1.85000E+01	-8.58307E-06	-3.99999E+00	-4.00000E+00	-9.88521E-05	3.15428E-03
1.90000E+01	-6.67572E-06	-3.99999E+00	-4.00000E+00	-1.37368E-04	-2.99817E-04
1.95000E+01	-6.67572E-06	-3.99999E+00	-4.00000E+00	-2.92132E-05	-3.47883E-03
2.00000E+01	-6.67572E-06	-3.99999E+00	-4.00000E+00	-4.11578E-04	-3.62083E-03
2.05000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	-2.07481E-04	-5.98532E-04
2.10000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	4.47285E-05	2.95728E-03
2.15000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	-3.50278E-05	3.91476E-03
2.20000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	2.75278E-05	1.44177E-03
2.25000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	2.86666E-05	-2.28600E-03
2.30000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	6.14717E-05	-4.02098E-03
2.35000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	-1.58761E-04	-2.22983E-03
2.40000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	-3.92178E-04	1.50851E-03
2.45000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	7.16922E-06	3.92949E-03
2.50000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	1.14060E-04	2.90950E-03
2.55000E+01	-5.00679E-06	-3.99999E+00	-4.00000E+00	-1.00049E-04	-6.45998E-04

**** SYSL/PC SIMULATOR OUTPUT -- 02-AUG-1994 12:07:57

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	ERROR	POS	CONT_POS	ACCEL	X
2.60000E+01	-4.52995E-06	-4.00000E+00	-4.00000E+00	3.10953E-05	-3.64166E-03
2.65000E+01	-4.52995E-06	-4.00000E+00	-4.00000E+00	1.04454E-04	-3.46193E-03
2.70000E+01	-4.52995E-06	-4.00000E+00	-4.00000E+00	-2.41870E-05	-2.51252E-04
2.75000E+01	-4.29153E-06	-4.00000E+00	-4.00000E+00	-2.15080E-04	3.16933E-03
2.80000E+01	-4.05312E-06	-4.00000E+00	-4.00000E+00	-2.09818E-04	3.83044E-03
2.85000E+01	-4.05312E-06	-4.00000E+00	-4.00000E+00	3.26051E-04	1.13694E-03
2.90000E+01	-4.05312E-06	-4.00000E+00	-4.00000E+00	3.79768E-05	-2.55078E-03
2.95000E+01	-4.05312E-06	-4.00000E+00	-4.00000E+00	-1.42335E-04	-4.00352E-03
3.00000E+01	-4.05312E-06	-4.00000E+00	-4.00000E+00	-1.12445E-04	-1.94448E-03

SIMULATION TIME =   80.631 SECONDS, UPDATE CALLS--361417, INTEGRATION STEPS-- 61

GRAPH PREPARATION TIME =   4.558 SECONDS

```
*.....PROGRAM NAG.DAT (STUDY CASE 1: GRIPPER AXIS)
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER

INTGER INIT_SEQ

INITIAL
      DELS=TSAMP
      INIT_SEQ=0
DYNAMIC
*
*-----DIGITAL PID CONTROLLER
*
      TARG_P1=STEP(0.1)-STEP(10.2852)-STEP(15.4704)
      TARG_POS=0.7*TARG_P1
*
NOSORT
      TEST=SAMPLE(0.0,FINTIM,TSAMP)
      IF(TEST.EQ.0.0) GO TO 10
*-----SEQUENCER(INITIALIZE ON FIRST PASS ONLY)
      IF(INIT_SEQ.EQ.1) GO TO 20
      INIT_SEQ=1
      INTG_PRE=0.0
      LAST_POS=0.0
      CONT_POS=POS
      CONT_SPD=0.0
      PRES_POS=POS
      TARG_PRE=TARG_POS
   20 CONTINUE
*-----PROFILE
      IF(TARG_POS.EQ.TARG_PRE) GO TO 50
      IF(TARG_POS.GT.TARG_PRE) CONT_SPD=MAX_SPD
      IF(TARG_POS.LT.TARG_PRE) CONT_SPD=-MAX_SPD
      TARG_PRE=TARG_POS
      PHASE=0.0
   50 CONTINUE
      IF(ABS(CONT_POS-TARG_POS).LE.1.0E-4) THEN
                                             PHASE=1.0
                                             CONT_SPD=0.0
                                             CONT_POS=TARG_POS
                                             ENDIF
      PRES_POS=POS
      CONT_POS=CONT_POS+CONT_SPD*TSAMP
*-----ERROR
      ERROR=CONT_POS-PRES_POS
*-----INTEGRATE
      INTG=INTG_PRE+PHASE*ERROR*IFACTOR/ISCALE
      INTG_PRE=INTG
      INTG_LIM=PHASE*LIMIT(-ILIMIT,ILIMIT,INTG)
*-----TACH
      SPEED=(PRES_POS-LAST_POS)/TSAMP
      LAST_POS=PRES_POS
*-----PROPORTION
      PROP=ERROR*PFACTOR/PSCALE
*-----DERIVE
      DERIV=SPEED*DFACTOR/DSCALE
*     PID
      VOLTAGE=LIMIT(-MAX_VOLT,MAX_VOLT,PROP+INTG_LIM-DERIV)
   10 CONTINUE
SORT
```

```
      E2=VOLTAGE-KB*OMEGA
      C1=REALPL(0.0,L/R,(1/R)*E2)
      C1_LIM=LIMIT(-MAX_CURR,MAX_CURR,C1)
      TM=KT*C1_LIM
      C2=TM-TL
      OMEGA=REALPL(0.0,J/F,(1/F)*C2)
      THETA=INTGRL(0.0,OMEGA)
      POS=KF*THETA

PARAM IFACTOR=0.001, ISCALE=1.0, DFACTOR=.15, DSCALE=1.0,...
      PFACTOR=720.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=0.135,...
      MAX_VOLT=28, TSAMP=0.005,KB=0.034, L=1.2E-3, R=3.7,...
      MAX_CURR=1.0, KT=4.8, TL=0, F=6.589E-4, J=1.3E-4, KF=1.9894E-4


INTEG RKM
TIMER DELT=0.0001, FINTIM=30.0, DELPR=1.0, DELGR=0.1
PRINT ERROR,POS,CONT_POS
*INTG_LIM
*PRINT CONT_POS,POS,X
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED
*        ,X,ACCEL
PLOTS STRIP,MODEL=97,IOPORT=97
*PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
GRAPH TIME, PHASE,TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
*GRAPH TIME, X, ACCEL
*GRAPH TIME,C1_LIM,VOLTAGE,INTG_LIM
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),...
      C1_LIM(AMPERE),VOLTAGE(VOLT)
*       ,X(INCH),ACCEL(INCH/SEC^2)
END
STOP
```

```
                    **** SYSL/PC SIMULATION DATA ****
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER
PARAM IFACTOR=0.001, ISCALE=1.0, DFACTOR=.15, DSCALE=1.0,...
      PFACTOR=720.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=0.135,...
      MAX_VOLT=28, TSAMP=0.005,KB=0.034, L=1.2E-3, R=3.7,...
      MAX_CURR=1.0, KT=4.8, TL=0, F=6.589E-4, J=1.3E-4, KF=1.9894E-4
INTEG RKM
TIMER DELT=0.0001, FINTIM=30.0, DELPR=1.0, DELGR=0.1
PRINT ERROR,POS,CONT_POS
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
        VOLTAGE, INTG_LIM,SPEED
PLOTS STRIP,MODEL=97,IOPORT=97
GRAPH TIME, PHASE,TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),...
      C1_LIM(AMPERE),VOLTAGE(VOLT)
END
```

**** SYSL/PC SIMULATOR OUTPUT -- 10-AUG-1994 11:28:40

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	ERROR	POS	CONT_POS
0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01
1.00000E+00	3.19656E-02	9.02169E-02	1.22175E-01
2.00000E+00	3.26412E-02	2.24532E-01	2.57174E-01
3.00000E+00	3.26600E-02	3.59512E-01	3.92172E-01
4.00000E+00	3.26577E-02	4.94514E-01	5.27172E-01
5.00000E+00	3.26575E-02	6.29519E-01	6.62176E-01
6.00000E+00	1.53476E-03	6.98465E-01	7.00000E-01
7.00000E+00	1.99676E-05	6.99980E-01	7.00000E-01
8.00000E+00	9.53674E-07	6.99999E-01	7.00000E-01
9.00000E+00	7.15256E-07	6.99999E-01	7.00000E-01
1.00000E+01	7.15256E-07	6.99999E-01	7.00000E-01
1.10000E+01	-3.11106E-02	6.33906E-01	6.02797E-01
1.20000E+01	-3.26307E-02	5.00424E-01	4.67794E-01
1.30000E+01	-3.26415E-02	3.65437E-01	3.32795E-01
1.40000E+01	-3.26504E-02	2.30447E-01	1.97797E-01
1.50000E+01	-3.26554E-02	9.54526E-02	6.27973E-02
1.60000E+01	-3.25689E-02	-3.89811E-02	-7.15500E-02
1.70000E+01	-3.26564E-02	-1.73893E-01	-2.06549E-01
1.80000E+01	-3.26550E-02	-3.08893E-01	-3.41548E-01
1.90000E+01	-3.26443E-02	-4.43902E-01	-4.76546E-01
2.00000E+01	-3.26580E-02	-5.78892E-01	-6.11550E-01
2.10000E+01	-7.55405E-03	-6.92446E-01	-7.00000E-01
2.20000E+01	-1.07944E-04	-6.99892E-01	-7.00000E-01
2.30000E+01	-3.27826E-06	-6.99997E-01	-7.00000E-01
2.40000E+01	-2.98023E-06	-6.99997E-01	-7.00000E-01
2.50000E+01	-2.80142E-06	-6.99997E-01	-7.00000E-01
2.60000E+01	-2.68221E-06	-6.99997E-01	-7.00000E-01
2.70000E+01	-2.68221E-06	-6.99997E-01	-7.00000E-01
2.80000E+01	-2.56300E-06	-6.99997E-01	-7.00000E-01
2.90000E+01	-2.56300E-06	-6.99997E-01	-7.00000E-01
3.00000E+01	-2.56300E-06	-6.99997E-01	-7.00000E-01

SIMULATION TIME =   32.900 SECONDS, UPDATE CALLS--195324, INTEGRATION STEPS-- 32
*** STRIP PLOTTING NOT AVAILABLE ***
*** STRIP PLOTTING NOT AVAILABLE ***

GRAPH PREPARATION TIME =   0.001 SECONDS

```
*.....PROGRAM NAE1.DAT (STUDY CASE 2: ELEVATION AXIS)
*.....WITH KP=900, KI=0.01, KR=0.015, Max_spd = 1.7087 (INCH/SEC)
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER

INTGER INIT_SEQ

INITIAL
      DELS=TSAMP
      INIT_SEQ=0
DYNAMIC
*
*-----DIGITAL PID CONTROLLER
*
      TARG_P1=STEP(0.01)
      TARG_POS=LTH*TARG_P1
*
NOSORT
      TEST=SAMPLE(0.0,FINTIM,TSAMP)
      IF(TEST.EQ.0.0) GO TO 10
*-----SEQUENCER(INITIALIZE ON FIRST PASS ONLY)
      IF(INIT_SEQ.EQ.1) GO TO 20
      INIT_SEQ=1
      INTG_PRE=0.0
      LAST_POS=0.0
      CONT_POS=POS
      CONT_SPD=0.0
      PRES_POS=POS
      TARG_PRE=TARG_POS
   20 CONTINUE
*-----PROFILE
      IF(TARG_POS.EQ.TARG_PRE) GO TO 50
      IF(TARG_POS.GT.TARG_PRE) CONT_SPD=MAX_SPD
      IF(TARG_POS.LT.TARG_PRE) CONT_SPD=-MAX_SPD
      TARG_PRE=TARG_POS
      PHASE=0.0
   50 CONTINUE
      IF(ABS(CONT_POS-TARG_POS).LT.6.0E-3) THEN
                                     PHASE=1.0
                                     CONT_SPD=0.0
                                     CONT_POS=TARG_POS
                                     ENDIF
      PRES_POS=POS
      CONT_POS=CONT_POS+CONT_SPD*TSAMP
*-----ERROR
      ERROR=CONT_POS-PRES_POS
*-----INTEGRATE
      INTG=INTG_PRE+ERROR*IFACTOR/ISCALE
      INTG_PRE=INTG
      INTG_LIM=LIMIT(-ILIMIT,ILIMIT,INTG)
*-----TACH
      SPEED=(PRES_POS-LAST_POS)/TSAMP
      LAST_POS=PRES_POS
*-----PROPORTION
      PROP=ERROR*PFACTOR/PSCALE
*-----DERIVE
      DERIV=SPEED*DFACTOR/DSCALE
*     PID
      VOLTAGE=LIMIT(-MAX_VOLT,MAX_VOLT,PROP+INTG_LIM-DERIV)
   10 CONTINUE
```

```
SORT
      E2=VOLTAGE-KB*OMEGA
      C1=REALPL(0.0,L/R,(1/R)*E2)
      C1_LIM=LIMIT(-MAX_CURR,MAX_CURR,C1)
      TM=KT*C1_LIM
      C2=TM-TL
      FORCE=K*(POS-X)
      TL=FORCE*16*KF
      OMEGA=REALPL(0.0,J/F,(1/F)*C2)
      THETA=INTGRL(0.0,OMEGA)
      POS=KF*THETA
      ACCEL=KF*(C2-F*OMEGA)/J
      XDOT=INTGRL(0.0,(-K*X)/M-ACCEL)
      X   =INTGRL(A,XDOT)
INCON A=0.0
CONST M=3.5742E-2
PARAM LTH=0.125,IFACTOR=.01, ISCALE=1.0, DFACTOR=.015, DSCALE=1.0,...
      PFACTOR=900.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=1.7087,...
      MAX_VOLT=28.0, TSAMP=0.005,KB=0.169, L=1.8E-3, R=2.5,...
      MAX_CURR=1.5, KT=24.0, F=0.0162, J=5.0E-3, KF=.01253,K=52
INTEG RKM
TIMER DELT=0.001, FINTIM=5, DELPR=.1, DELGR=0.01
*PRINT POS,ERROR,CONT_POS,TM,TL
PRINT CONT_POS,POS,ERROR,FORCE,X
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X,FORCE
PLOTS STRIP,MODEL=97,IOPORT=97
*PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
GRAPH TIME, PHASE, TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
*GRAPH TIME,C1_LIM,VOLTAGE,INTG_LIM
GRAPH TIME, ACCEL, FORCE, X
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),FORCE(LB)
END
STOP
```

```
                    **** SYSL/PC SIMULATION DATA ****
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER
INCON A=0.0
CONST M=3.5742E-2
PARAM LTH=0.125,IFACTOR=.01, ISCALE=1.0, DFACTOR=.015, DSCALE=1.0,...
      PFACTOR=900.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=1.7087,...
      MAX_VOLT=28.0, TSAMP=0.005,KB=0.169, L=1.8E-3, R=2.5,...
      MAX_CURR=1.5, KT=24.0, F=0.0162, J=5.0E-3, KF=.01253,K=52
INTEG RKM
TIMER DELT=0.001, FINTIM=5, DELPR=.1, DELGR=0.01
PRINT CONT_POS,POS,ERROR,FORCE,X
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X,FORCE
PLOTS STRIP,MODEL=97,IOPORT=97
GRAPH TIME, PHASE, TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
GRAPH TIME, ACCEL, FORCE, X
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),FORCE(LB)
END
```

**** SYSL/PC SIMULATOR OUTPUT -- 29-JUL-1994 13:34:29

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	CONT_POS	POS	ERROR	FORCE	X
0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01
1.00000E-01	1.25000E-01	1.23692E-01	1.30832E-03	6.05096E+00	7.32704E-03
2.00000E-01	1.25000E-01	1.24824E-01	1.75662E-04	9.49403E+00	-5.77532E-02
3.00000E-01	1.25000E-01	1.24935E-01	6.48052E-05	2.11566E+00	8.42495E-02
4.00000E-01	1.25000E-01	1.24755E-01	2.45057E-04	1.03473E+01	-7.42318E-02
5.00000E-01	1.25000E-01	1.24927E-01	7.33510E-05	4.82670E+00	3.21054E-02
6.00000E-01	1.25000E-01	1.24837E-01	1.62624E-04	5.25204E+00	2.38365E-02
7.00000E-01	1.25000E-01	1.24806E-01	1.94326E-04	1.00963E+01	-6.93549E-02
8.00000E-01	1.25000E-01	1.24945E-01	5.48437E-05	2.08913E+00	8.47695E-02
9.00000E-01	1.25000E-01	1.24759E-01	2.40572E-04	9.78781E+00	-6.34677E-02
1.00000E+00	1.25000E-01	1.24911E-01	8.88258E-05	5.72909E+00	1.47363E-02
1.10000E+00	1.25000E-01	1.24859E-01	1.40734E-04	4.39815E+00	4.02794E-02
1.20000E+00	1.25000E-01	1.24789E-01	2.10963E-04	1.05324E+01	-7.77580E-02
1.30000E+00	1.25000E-01	1.24950E-01	4.99040E-05	2.25883E+00	8.15110E-02
1.40000E+00	1.25000E-01	1.24768E-01	2.32123E-04	9.08682E+00	-4.99787E-02
1.50000E+00	1.25000E-01	1.24892E-01	1.07661E-04	6.65693E+00	-3.12551E-03
1.60000E+00	1.25000E-01	1.24880E-01	1.20424E-04	3.64541E+00	5.47756E-02
1.70000E+00	1.25000E-01	1.24775E-01	2.24560E-04	1.07846E+01	-8.26203E-02
1.80000E+00	1.25000E-01	1.24952E-01	4.83543E-05	2.61548E+00	7.46539E-02
1.90000E+00	1.25000E-01	1.24780E-01	2.20053E-04	8.27696E+00	-3.43923E-02
2.00000E+00	1.25000E-01	1.24873E-01	1.27114E-04	7.56868E+00	-2.06787E-02
2.10000E+00	1.25000E-01	1.24899E-01	1.01149E-04	3.02670E+00	6.66931E-02
2.20000E+00	1.25000E-01	1.24765E-01	2.34589E-04	1.08432E+01	-8.37571E-02
2.30000E+00	1.25000E-01	1.24948E-01	5.16847E-05	3.14122E+00	6.45403E-02
2.40000E+00	1.25000E-01	1.24795E-01	2.04951E-04	7.39555E+00	-1.74271E-02
2.50000E+00	1.25000E-01	1.24852E-01	1.47603E-04	8.42345E+00	-3.71370E-02
2.60000E+00	1.25000E-01	1.24916E-01	8.41394E-05	2.56823E+00	7.55269E-02
2.70000E+00	1.25000E-01	1.24760E-01	2.39775E-04	1.07077E+01	-8.11561E-02
2.80000E+00	1.25000E-01	1.24941E-01	5.91576E-05	3.81100E+00	5.16524E-02
2.90000E+00	1.25000E-01	1.24813E-01	1.87337E-04	6.48239E+00	1.51268E-04
3.00000E+00	1.25000E-01	1.24832E-01	1.67683E-04	9.18447E+00	-5.17921E-02
3.10000E+00	1.25000E-01	1.24930E-01	6.99833E-05	2.28869E+00	8.09168E-02
3.20000E+00	1.25000E-01	1.24758E-01	2.41697E-04	1.03856E+01	-7.49643E-02
3.30000E+00	1.25000E-01	1.24930E-01	6.98119E-05	4.59439E+00	3.65765E-02
3.40000E+00	1.25000E-01	1.24832E-01	1.67601E-04	5.57757E+00	1.75715E-02
3.50000E+00	1.25000E-01	1.24814E-01	1.86443E-04	9.81872E+00	-6.40080E-02
3.60000E+00	1.25000E-01	1.24941E-01	5.91651E-05	2.19891E+00	8.26541E-02
3.70000E+00	1.25000E-01	1.24761E-01	2.38791E-04	9.89310E+00	-6.54908E-02
3.80000E+00	1.25000E-01	1.24915E-01	8.45343E-05	5.45476E+00	2.00162E-02
3.90000E+00	1.25000E-01	1.24853E-01	1.47000E-04	4.72237E+00	3.40383E-02
4.00000E+00	1.25000E-01	1.24797E-01	2.02931E-04	1.02987E+01	-7.32552E-02
4.10000E+00	1.25000E-01	1.24947E-01	5.29662E-05	2.30117E+00	8.06938E-02
4.20000E+00	1.25000E-01	1.24768E-01	2.32041E-04	9.25403E+00	-5.31942E-02
4.30000E+00	1.25000E-01	1.24899E-01	1.00911E-04	6.35293E+00	2.72742E-03
4.40000E+00	1.25000E-01	1.24873E-01	1.27017E-04	3.95431E+00	4.88286E-02
4.50000E+00	1.25000E-01	1.24783E-01	2.17490E-04	1.06045E+01	-7.91493E-02
4.60000E+00	1.25000E-01	1.24950E-01	5.00157E-05	2.58922E+00	7.51574E-02
4.70000E+00	1.25000E-01	1.24779E-01	2.21118E-04	8.49802E+00	-3.86445E-02
4.80000E+00	1.25000E-01	1.24880E-01	1.20275E-04	7.24899E+00	-1.45240E-02
4.90000E+00	1.25000E-01	1.24892E-01	1.07542E-04	3.30649E+00	6.13060E-02
5.00000E+00	1.25000E-01	1.24772E-01	2.28375E-04	1.07243E+01	-8.14647E-02

SIMULATION TIME = 5.549 SECONDS, UPDATE CALLS-- 25130, INTEGRATION STEPS-- 4

```
*.....PROGRAM NAE1.DAT (STUDY CASE 2: ELEVATION AXIS)
*.....WITH KP=900, KI=0.01, KR=0.015, Max_spd=0.7087 (INCH/SEC)
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER

INTGER INIT_SEQ

INITIAL
      DELS=TSAMP
      INIT_SEQ=0
DYNAMIC
*
*-----DIGITAL PID CONTROLLER
*
      TARG_P1=STEP(0.01)
      TARG_POS=LTH*TARG_P1
*
NOSORT
      TEST=SAMPLE(0.0,FINTIM,TSAMP)
      IF(TEST.EQ.0.0) GO TO 10
*-----SEQUENCER(INITIALIZE ON FIRST PASS ONLY)
      IF(INIT_SEQ.EQ.1) GO TO 20
      INIT_SEQ=1
      INTG_PRE=0.0
      LAST_POS=0.0
      CONT_POS=POS
      CONT_SPD=0.0
      PRES_POS=POS
      TARG_PRE=TARG_POS
   20 CONTINUE
*-----PROFILE
      IF(TARG_POS.EQ.TARG_PRE) GO TO 50
      IF(TARG_POS.GT.TARG_PRE) CONT_SPD=MAX_SPD
      IF(TARG_POS.LT.TARG_PRE) CONT_SPD=-MAX_SPD
      TARG_PRE=TARG_POS
      PHASE=0.0
   50 CONTINUE
      IF(ABS(CONT_POS-TARG_POS).LT.6.0E-3) THEN
                                            PHASE=1.0
                                            CONT_SPD=0.0
                                            CONT_POS=TARG_POS
                                            ENDIF
      PRES_POS=POS
      CONT_POS=CONT_POS+CONT_SPD*TSAMP
*-----ERROR
      ERROR=CONT_POS-PRES_POS
*-----INTEGRATE
      INTG=INTG_PRE+ERROR*IFACTOR/ISCALE
      INTG_PRE=INTG
      INTG_LIM=LIMIT(-ILIMIT,ILIMIT,INTG)
*-----TACH
      SPEED=(PRES_POS-LAST_POS)/TSAMP
      LAST_POS=PRES_POS
*-----PROPORTION
      PROP=ERROR*PFACTOR/PSCALE
*-----DERIVE
      DERIV=SPEED*DFACTOR/DSCALE
*     PID
      VOLTAGE=LIMIT(-MAX_VOLT,MAX_VOLT,PROP+INTG_LIM-DERIV)
   10 CONTINUE
```

```
SORT
      E2=VOLTAGE-KB*OMEGA
      C1=REALPL(0.0,L/R,(1/R)*E2)
      C1_LIM=LIMIT(-MAX_CURR,MAX_CURR,C1)
      TM=KT*C1_LIM
      C2=TM-TL
      FORCE=K*(POS-X)
      TL=FORCE*16*KF
      OMEGA=REALPL(0.0,J/F,(1/F)*C2)
      THETA=INTGRL(0.0,OMEGA)
      POS=KF*THETA
      ACCEL=KF*(C2-F*OMEGA)/J
      XDOT=INTGRL(0.0,(-K*X)/M-ACCEL)
      X    =INTGRL(A,XDOT)
INCON A=0.0
CONST M=3.5742E-2
PARAM LTH=0.125,IFACTOR=.01, ISCALE=1.0, DFACTOR=.015, DSCALE=1.0,...
      PFACTOR=900.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=0.7087,...
      MAX_VOLT=28.0, TSAMP=0.005,KB=0.169, L=1.8E-3, R=2.5,...
      MAX_CURR=1.5, KT=24.0, F=0.0162, J=5.0E-3, KF=.01253,K=52
INTEG RKM
TIMER DELT=0.001, FINTIM=5, DELPR=.1, DELGR=0.01
*PRINT POS,ERROR,CONT_POS,TM,TL
PRINT CONT_POS,POS,ERROR,FORCE,X
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X,FORCE
PLOTS STRIP,MODEL=97,IOPORT=97
*PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
GRAPH TIME, PHASE, TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
*GRAPH TIME,C1_LIM,VOLTAGE,INTG_LIM
GRAPH TIME, ACCEL, FORCE, X
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),FORCE(LB)
END
STOP
```

```
                  **** SYSL/PC SIMULATION DATA ****

TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER
INCON A=0.0
CONST M=3.5742E-2
PARAM LTH=0.125,IFACTOR=.01, ISCALE=1.0, DFACTOR=.015, DSCALE=1.0,...
      PFACTOR=900.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=0.7087,...
      MAX_VOLT=28.0, TSAMP=0.005,KB=0.169, L=1.8E-3, R=2.5,...
      MAX_CURR=1.5, KT=24.0, F=0.0162, J=5.0E-3, KF=.01253,K=52
INTEG RKM
TIMER DELT=0.001, FINTIM=5, DELPR=.1, DELGR=0.01
PRINT CONT_POS,POS,ERROR,FORCE,X
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X,FORCE
PLOTS STRIP,MODEL=97,IOPORT=97
GRAPH TIME, PHASE, TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
GRAPH TIME, ACCEL, FORCE, X
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),FORCE(LB)
END
```

**** SYSL/PC SIMULATOR OUTPUT -- 29-JUL-1994 13:36:10

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	CONT_POS	POS	ERROR	FORCE	X
0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01
1.00000E-01	6.73265E-02	5.63752E-02	1.09513E-02	3.03134E+00	-1.91988E-03
2.00000E-01	1.25000E-01	1.23640E-01	1.36030E-03	6.75008E+00	-6.16959E-03
3.00000E-01	1.25000E-01	1.24861E-01	1.38856E-04	6.28226E+00	4.04850E-03
4.00000E-01	1.25000E-01	1.24851E-01	1.49243E-04	6.44088E+00	9.87777E-04
5.00000E-01	1.25000E-01	1.24851E-01	1.49377E-04	6.78275E+00	-5.58695E-03
6.00000E-01	1.25000E-01	1.24861E-01	1.38618E-04	6.08931E+00	7.75917E-03
7.00000E-01	1.25000E-01	1.24845E-01	1.55278E-04	6.83352E+00	-6.56908E-03
8.00000E-01	1.25000E-01	1.24860E-01	1.39922E-04	6.36073E+00	2.53828E-03
9.00000E-01	1.25000E-01	1.24853E-01	1.47186E-04	6.35800E+00	2.58360E-03
1.00000E+00	1.25000E-01	1.24849E-01	1.50919E-04	6.83418E+00	-6.57754E-03
1.10000E+00	1.25000E-01	1.24862E-01	1.37605E-04	6.09157E+00	7.71685E-03
1.20000E+00	1.25000E-01	1.24845E-01	1.54607E-04	6.77870E+00	-5.51427E-03
1.30000E+00	1.25000E-01	1.24859E-01	1.41323E-04	6.44434E+00	9.29081E-04
1.40000E+00	1.25000E-01	1.24855E-01	1.45160E-04	6.28187E+00	4.04959E-03
1.50000E+00	1.25000E-01	1.24848E-01	1.52364E-04	6.86990E+00	-7.26578E-03
1.60000E+00	1.25000E-01	1.24863E-01	1.37113E-04	6.11164E+00	7.33128E-03
1.70000E+00	1.25000E-01	1.24846E-01	1.53609E-04	6.71163E+00	-4.22338E-03
1.80000E+00	1.25000E-01	1.24857E-01	1.42872E-04	6.52930E+00	-7.06395E-04
1.90000E+00	1.25000E-01	1.24857E-01	1.43170E-04	6.21585E+00	5.32124E-03
2.00000E+00	1.25000E-01	1.24847E-01	1.53258E-04	6.88849E+00	-7.62413E-03
2.10000E+00	1.25000E-01	1.24863E-01	1.36934E-04	6.14849E+00	6.62282E-03
2.20000E+00	1.25000E-01	1.24848E-01	1.52186E-04	6.63546E+00	-2.75709E-03
2.30000E+00	1.25000E-01	1.24856E-01	1.44497E-04	6.61182E+00	-2.29494E-03
2.40000E+00	1.25000E-01	1.24859E-01	1.41323E-04	6.16278E+00	6.34366E-03
2.50000E+00	1.25000E-01	1.24846E-01	1.53929E-04	6.88923E+00	-7.63919E-03
2.60000E+00	1.25000E-01	1.24863E-01	1.37188E-04	6.20032E+00	5.62586E-03
2.70000E+00	1.25000E-01	1.24849E-01	1.50643E-04	6.55361E+00	-1.18157E-03
2.80000E+00	1.25000E-01	1.24854E-01	1.46173E-04	6.68823E+00	-3.76590E-03
2.90000E+00	1.25000E-01	1.24860E-01	1.39609E-04	6.12491E+00	7.07362E-03
3.00000E+00	1.25000E-01	1.24846E-01	1.54227E-04	6.87230E+00	-7.31384E-03
3.10000E+00	1.25000E-01	1.24862E-01	1.37821E-04	6.26465E+00	4.38807E-03
3.20000E+00	1.25000E-01	1.24851E-01	1.48810E-04	6.46984E+00	4.31208E-04
3.30000E+00	1.25000E-01	1.24852E-01	1.47834E-04	6.75516E+00	-5.05466E-03
3.40000E+00	1.25000E-01	1.24862E-01	1.38260E-04	6.10376E+00	7.48175E-03
3.50000E+00	1.25000E-01	1.24846E-01	1.54153E-04	6.83862E+00	-6.66603E-03
3.60000E+00	1.25000E-01	1.24861E-01	1.38752E-04	6.33851E+00	2.96686E-03
3.70000E+00	1.25000E-01	1.24853E-01	1.46866E-04	6.38788E+00	2.00924E-03
3.80000E+00	1.25000E-01	1.24851E-01	1.49362E-04	6.80976E+00	-6.10631E-03
3.90000E+00	1.25000E-01	1.24863E-01	1.37225E-04	6.10012E+00	7.55273E-03
4.00000E+00	1.25000E-01	1.24846E-01	1.53653E-04	6.78983E+00	-5.72729E-03
4.10000E+00	1.25000E-01	1.24860E-01	1.39982E-04	6.41851E+00	1.42710E-03
4.20000E+00	1.25000E-01	1.24855E-01	1.44891E-04	6.31137E+00	3.48262E-03
4.30000E+00	1.25000E-01	1.24849E-01	1.50710E-04	6.84970E+00	-6.87575E-03
4.40000E+00	1.25000E-01	1.24863E-01	1.36562E-04	6.11398E+00	7.28694E-03
4.50000E+00	1.25000E-01	1.24847E-01	1.52759E-04	6.72832E+00	-4.54347E-03
4.60000E+00	1.25000E-01	1.24859E-01	1.41442E-04	6.50099E+00	-1.60389E-04
4.70000E+00	1.25000E-01	1.24857E-01	1.42910E-04	6.24367E+00	4.78659E-03
4.80000E+00	1.25000E-01	1.24848E-01	1.51798E-04	6.87338E+00	-7.33226E-03
4.90000E+00	1.25000E-01	1.24864E-01	1.36256E-04	6.14453E+00	6.69968E-03
5.00000E+00	1.25000E-01	1.24848E-01	1.51522E-04	6.65688E+00	-3.16855E-03

SIMULATION TIME = 4.229 SECONDS, UPDATE CALLS-- 18766, INTEGRATION STEPS-- 3

```
*.....PROGRAM NAE1.DAT (STUDY CASE 2: ELEVATION AXIS)
*.....WITH KP=440, KI=0.01, KR=15, Max_spd = 1.7087 (INCH/SEC)
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER

INTGER INIT_SEQ

INITIAL
      DELS=TSAMP
      INIT_SEQ=0
DYNAMIC
*
*-----DIGITAL PID CONTROLLER
*
      TARG_P1=STEP(0.01)
      TARG_POS=LTH*TARG_P1
*
NOSORT
      TEST=SAMPLE(0.0,FINTIM,TSAMP)
      IF(TEST.EQ.0.0) GO TO 10
*-----SEQUENCER(INITIALIZE ON FIRST PASS ONLY)
      IF(INIT_SEQ.EQ.1) GO TO 20
      INIT_SEQ=1
      INTG_PRE=0.0
      LAST_POS=0.0
      CONT_POS=POS
      CONT_SPD=0.0
      PRES_POS=POS
      TARG_PRE=TARG_POS
   20 CONTINUE
*-----PROFILE
      IF(TARG_POS.EQ.TARG_PRE) GO TO 50
      IF(TARG_POS.GT.TARG_PRE) CONT_SPD=MAX_SPD
      IF(TARG_POS.LT.TARG_PRE) CONT_SPD=-MAX_SPD
      TARG_PRE=TARG_POS
      PHASE=0.0
   50 CONTINUE
      IF(ABS(CONT_POS-TARG_POS).LT.6.0E-3) THEN
                                            PHASE=1.0
                                            CONT_SPD=0.0
                                            CONT_POS=TARG_POS
                                            ENDIF
      PRES_POS=POS
      CONT_POS=CONT_POS+CONT_SPD*TSAMP
*-----ERROR
      ERROR=CONT_POS-PRES_POS
*-----INTEGRATE
      INTG=INTG_PRE+ERROR*IFACTOR/ISCALE
      INTG_PRE=INTG
      INTG_LIM=LIMIT(-ILIMIT,ILIMIT,INTG)
*-----TACH
      SPEED=(PRES_POS-LAST_POS)/TSAMP
      LAST_POS=PRES_POS
*-----PROPORTION
      PROP=ERROR*PFACTOR/PSCALE
*-----DERIVE
      DERIV=SPEED*DFACTOR/DSCALE
*     PID
      VOLTAGE=LIMIT(-MAX_VOLT,MAX_VOLT,PROP+INTG_LIM-DERIV)
   10 CONTINUE
```

```
SORT
       E2=VOLTAGE-KB*OMEGA
       C1=REALPL(0.0,L/R,(1/R)*E2)
       C1_LIM=LIMIT(-MAX_CURR,MAX_CURR,C1)
       TM=KT*C1_LIM
       C2=TM-TL
       FORCE=K*(POS-X)
       TL=FORCE*16*KF
       OMEGA=REALPL(0.0,J/F,(1/F)*C2)
       THETA=INTGRL(0.0,OMEGA)
       POS=KF*THETA
       ACCEL=KF*(C2-F*OMEGA)/J
       XDOT=INTGRL(0.0,(-K*X)/M-ACCEL)
       X    =INTGRL(A,XDOT)
INCON A=0.0
CONST M=3.5742E-2
PARAM LTH=0.125,IFACTOR=.01, ISCALE=1.0, DFACTOR=15, DSCALE=1.0,...
      PFACTOR=440.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=1.7087,...
      MAX_VOLT=28.0, TSAMP=0.005,KB=0.169, L=1.8E-3, R=2.5,...
      MAX_CURR=1.5, KT=24.0, F=0.0162, J=5.0E-3, KF=.01253,K=52
INTEG RKM
TIMER DELT=0.001, FINTIM=5, DELPR=.1, DELGR=0.01
*PRINT POS,ERROR,CONT_POS,TM,TL
PRINT CONT_POS,POS,ERROR,FORCE,X
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X,FORCE
PLOTS STRIP,MODEL=97,IOPORT=97
*PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
GRAPH TIME, PHASE, TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
*GRAPH TIME,C1_LIM,VOLTAGE,INTG_LIM
GRAPH TIME, ACCEL, FORCE, X
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),FORCE(LB)
END
STOP
```

**** SYSL/PC SIMULATION DATA ****

```
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER
INCON A=0.0
CONST M=3.5742E-2
PARAM LTH=0.125,IFACTOR=.01, ISCALE=1.0, DFACTOR=15, DSCALE=1.0,...
      PFACTOR=440.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=1.7087,...
      MAX_VOLT=28.0, TSAMP=0.005,KB=0.169, L=1.8E-3, R=2.5,...
      MAX_CURR=1.5, KT=24.0, F=0.0162, J=5.0E-3, KF=.01253,K=52
INTEG RKM
TIMER DELT=0.001, FINTIM=5, DELPR=.1, DELGR=0.01
PRINT CONT_POS,POS,ERROR,FORCE,X
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X,FORCE
PLOTS STRIP,MODEL=97,IOPORT=97
GRAPH TIME, PHASE, TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
GRAPH TIME, ACCEL, FORCE, X
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),FORCE(LB)
END
```

**** SYSL/PC SIMULATOR OUTPUT -- 29-JUL-1994 13:37:39

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	CONT_POS	POS	ERROR	FORCE	X
0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01
1.00000E-01	1.25000E-01	7.07294E-02	5.42706E-02	4.22011E+00	-1.04265E-02
2.00000E-01	1.25000E-01	1.13704E-01	1.12963E-02	5.98771E+00	-1.44462E-03
3.00000E-01	1.25000E-01	1.22479E-01	2.52105E-03	5.13529E+00	2.37233E-02
4.00000E-01	1.25000E-01	1.24258E-01	7.41929E-04	8.20147E+00	-3.34626E-02
5.00000E-01	1.25000E-01	1.24662E-01	3.37854E-04	4.97015E+00	2.90823E-02
6.00000E-01	1.25000E-01	1.24678E-01	3.22439E-04	7.10761E+00	-1.20073E-02
7.00000E-01	1.25000E-01	1.24749E-01	2.50794E-04	7.01745E+00	-1.02017E-02
8.00000E-01	1.25000E-01	1.24724E-01	2.75619E-04	5.03410E+00	2.79148E-02
9.00000E-01	1.25000E-01	1.24714E-01	2.86460E-04	8.22482E+00	-3.34560E-02
1.00000E+00	1.25000E-01	1.24762E-01	2.37837E-04	5.21566E+00	2.44611E-02
1.10000E+00	1.25000E-01	1.24698E-01	3.01741E-04	6.73830E+00	-4.88452E-03
1.20000E+00	1.25000E-01	1.24747E-01	2.53111E-04	7.35779E+00	-1.67490E-02
1.30000E+00	1.25000E-01	1.24733E-01	2.67051E-04	4.87185E+00	3.10435E-02
1.40000E+00	1.25000E-01	1.24709E-01	2.91325E-04	8.13947E+00	-3.18196E-02
1.50000E+00	1.25000E-01	1.24762E-01	2.37703E-04	5.51077E+00	1.87859E-02
1.60000E+00	1.25000E-01	1.24703E-01	2.96913E-04	6.36203E+00	2.35637E-03
1.70000E+00	1.25000E-01	1.24743E-01	2.57365E-04	7.65175E+00	-2.24064E-02
1.80000E+00	1.25000E-01	1.24742E-01	2.58364E-04	4.78792E+00	3.26662E-02
1.90000E+00	1.25000E-01	1.24703E-01	2.96570E-04	7.97799E+00	-2.87194E-02
2.00000E+00	1.25000E-01	1.24762E-01	2.38277E-04	5.84670E+00	1.23251E-02
2.10000E+00	1.25000E-01	1.24708E-01	2.91944E-04	5.99784E+00	9.36490E-03
2.20000E+00	1.25000E-01	1.24736E-01	2.64294E-04	7.88607E+00	-2.69195E-02
2.30000E+00	1.25000E-01	1.24748E-01	2.52478E-04	4.78456E+00	3.27367E-02
2.40000E+00	1.25000E-01	1.24702E-01	2.97762E-04	7.74958E+00	-2.43282E-02
2.50000E+00	1.25000E-01	1.24762E-01	2.38158E-04	6.20727E+00	5.39117E-03
2.60000E+00	1.25000E-01	1.24713E-01	2.86542E-04	5.66241E+00	1.58209E-02
2.70000E+00	1.25000E-01	1.24729E-01	2.71283E-04	8.05113E+00	-3.01007E-02
2.80000E+00	1.25000E-01	1.24753E-01	2.46622E-04	4.86099E+00	3.12728E-02
2.90000E+00	1.25000E-01	1.24701E-01	2.99267E-04	7.46567E+00	-1.88698E-02
3.00000E+00	1.25000E-01	1.24760E-01	2.40311E-04	6.57489E+00	-1.68056E-03
3.10000E+00	1.25000E-01	1.24721E-01	2.78920E-04	5.37097E+00	2.14333E-02
3.20000E+00	1.25000E-01	1.24722E-01	2.78309E-04	8.14013E+00	-3.18193E-02
3.30000E+00	1.25000E-01	1.24760E-01	2.40088E-04	5.01254E+00	2.83650E-02
3.40000E+00	1.25000E-01	1.24700E-01	2.99774E-04	7.14045E+00	-1.26161E-02
3.50000E+00	1.25000E-01	1.24755E-01	2.44863E-04	6.93224E+00	-8.55721E-03
3.60000E+00	1.25000E-01	1.24727E-01	2.72587E-04	5.13655E+00	2.59475E-02
3.70000E+00	1.25000E-01	1.24718E-01	2.82302E-04	8.15042E+00	-3.20211E-02
3.80000E+00	1.25000E-01	1.24762E-01	2.38352E-04	5.23023E+00	2.41803E-02
3.90000E+00	1.25000E-01	1.24703E-01	2.96868E-04	6.79003E+00	-5.87428E-03
4.00000E+00	1.25000E-01	1.24752E-01	2.48045E-04	7.26292E+00	-1.49196E-02
4.10000E+00	1.25000E-01	1.24736E-01	2.63795E-04	4.96931E+00	2.91726E-02
4.20000E+00	1.25000E-01	1.24713E-01	2.86661E-04	8.08250E+00	-3.07193E-02
4.30000E+00	1.25000E-01	1.24765E-01	2.35073E-04	5.50344E+00	1.89296E-02
4.40000E+00	1.25000E-01	1.24707E-01	2.93322E-04	6.43101E+00	1.03341E-03
4.50000E+00	1.25000E-01	1.24745E-01	2.54773E-04	7.55178E+00	-2.04813E-02
4.60000E+00	1.25000E-01	1.24744E-01	2.55741E-04	4.87580E+00	3.09789E-02
4.70000E+00	1.25000E-01	1.24710E-01	2.90416E-04	7.94105E+00	-2.80029E-02
4.80000E+00	1.25000E-01	1.24766E-01	2.34313E-04	5.81793E+00	1.28825E-02
4.90000E+00	1.25000E-01	1.24712E-01	2.88144E-04	6.08049E+00	7.77941E-03
5.00000E+00	1.25000E-01	1.24740E-01	2.60398E-04	7.78627E+00	-2.49964E-02

SIMULATION TIME = 5.218 SECONDS, UPDATE CALLS-- 23651, INTEGRATION STEPS-- 4

```
*.....PROGRAM NAR1.DAT(STUDY CASE 3: RADIAL AXIS)
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER

INTGER INIT_SEQ

INITIAL
      DELS=TSAMP
      INIT_SEQ=0
DYNAMIC
*
*-----DIGITAL PID CONTROLLER
*
      TARG_P1=STEP(0.01)
      TARG_POS=1*TARG_P1
*
NOSORT
      TEST=SAMPLE(0.0,FINTIM,TSAMP)
      IF(TEST.EQ.0.0) GO TO 10
*-----SEQUENCER(INITIALIZE ON FIRST PASS ONLY)
      IF(INIT_SEQ.EQ.1) GO TO 20
      INIT_SEQ=1
      INTG_PRE=0.0
      LAST_POS=0.0
      CONT_POS=POS
      CONT_SPD=0.0
      PRES_POS=POS
      TARG_PRE=TARG_POS
   20 CONTINUE
*-----PROFILE
      IF(TARG_POS.EQ.TARG_PRE) GO TO 50
      IF(TARG_POS.GT.TARG_PRE) CONT_SPD=MAX_SPD
      IF(TARG_POS.LT.TARG_PRE) CONT_SPD=-MAX_SPD
      TARG_PRE=TARG_POS
      PHASE=0.0
   50 CONTINUE
      IF(ABS(CONT_POS-TARG_POS).LE.3.0E-3) THEN
                                           PHASE=1.0
                                           CONT_SPD=0.0
                                           CONT_POS=TARG_POS
                                           ENDIF
      PRES_POS=POS
      CONT_POS=CONT_POS+CONT_SPD*TSAMP
*-----ERROR
      ERROR=CONT_POS-PRES_POS
*-----INTEGRATE
      INTG=INTG_PRE+PHASE*ERROR*IFACTOR/ISCALE
      INTG_PRE=INTG
      INTG_LIM=PHASE*LIMIT(-ILIMIT,ILIMIT,INTG)
*-----TACH
      SPEED=(PRES_POS-LAST_POS)/TSAMP
      LAST_POS=PRES_POS
*-----PROPORTION
      PROP=ERROR*PFACTOR/PSCALE
*-----DERIVE
      DERIV=SPEED*DFACTOR/DSCALE
*     PID
      VOLTAGE=LIMIT(-MAX_VOLT,MAX_VOLT,PROP+INTG_LIM-DERIV)
   10 CONTINUE
SORT
```

```
      E2=VOLTAGE-KB*OMEGA
      C1=REALPL(0.0,L/R,(1/R)*E2)
      C1_LIM=LIMIT(-MAX_CURR,MAX_CURR,C1)
      TM=KT*C1_LIM
      C2=TM-TL
      OMEGA=REALPL(0.0,J/F,(1/F)*C2)
      THETA=INTGRL(0.0,OMEGA)
      POS=KF*THETA
      ACCEL=KF*(C2-F*OMEGA)/J
      XDOT=INTGRL(0.0,(-K*X)/M-ACCEL)
      X   =INTGRL(A,XDOT)
INCON A=7.3529411E-2
CONST M=6.475E-3
PARAM IFACTOR=.01, ISCALE=1.0, DFACTOR=.01, DSCALE=1.0,...
      PFACTOR=600.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=0.9252,...
      MAX_VOLT=28, TSAMP=0.005,KB=0.016, L=0.55E-3, R=3.86,...
      MAX_CURR=0.45, KT=2.2, TL=0, F=1.1841E-4, J=2.67E-5,...
      KF=6.2659E-4 ,K=68

INTEG RKM
TIMER DELT=0.0001, FINTIM=30.0, DELPR=0.5, DELGR=0.1
PRINT ERROR,POS,CONT_POS,ACCEL,X
*PRINT POS,ERROR,VOLTAGE,C1_LIM,INTG_LIM
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X
*PLOTS STRIP,MODEL=97,IOPORT=97
PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
GRAPH TIME, PHASE, TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
*GRAPH TIME,C1_LIM,VOLTAGE,INTG_LIM
GRAPH TIME,SPEED,ACCEL,X
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),...
      C1_LIM(AMPERE),VOLTAGE(VOLT),SPEED(INCH/SECOND),...
      ACCEL(INCH/SECOND2),X(INCH)

END
STOP
```

**** SYSL/PC SIMULATION DATA ****

```
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER
INCON A=7.3529411E-2
CONST M=6.475E-3
PARAM IFACTOR=.01, ISCALE=1.0, DFACTOR=.01, DSCALE=1.0,...
      PFACTOR=600.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=0.9252,...
      MAX_VOLT=28, TSAMP=0.005,KB=0.016, L=0.55E-3, R=3.86,...
      MAX_CURR=0.45, KT=2.2, TL=0, F=1.1841E-4, J=2.67E-5,...
      KF=6.2659E-4 ,K=68
INTEG RKM
TIMER DELT=0.0001, FINTIM=30.0, DELPR=0.5, DELGR=0.1
PRINT ERROR,POS,CONT_POS,ACCEL,X
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,C1_LIM,...
       VOLTAGE, INTG_LIM,SPEED,ACCEL,X
PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
GRAPH TIME, PHASE, TARG_POS, CONT_SPD
GRAPH TIME, ERROR, POS, CONT_POS
GRAPH TIME,SPEED,ACCEL,X
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),...
      C1_LIM(AMPERE),VOLTAGE(VOLT),SPEED(INCH/SECOND),...
      ACCEL(INCH/SECOND2),X(INCH)
END
```

**** SYSL/PC SIMULATOR OUTPUT -- 02-AUG-1994 11:54:41

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	ERROR	POS	CONT_POS	ACCEL	X
0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	7.35294E-02
5.00000E-01	4.01560E-02	4.17818E-01	4.57974E-01	1.52717E-01	4.36849E-02
1.00000E+00	4.01346E-02	8.80438E-01	9.20572E-01	-4.17917E-03	-2.57533E-02
1.50000E+00	-2.62260E-06	1.00000E+00	1.00000E+00	-2.90438E-05	-7.20738E-02
2.00000E+00	-2.86102E-06	1.00000E+00	1.00000E+00	6.97384E-05	-5.73450E-02
2.50000E+00	-2.98023E-06	1.00000E+00	1.00000E+00	-2.95210E-05	7.61731E-03
3.00000E+00	-2.98023E-06	1.00000E+00	1.00000E+00	2.55921E-05	6.59102E-02
3.50000E+00	-3.09944E-06	1.00000E+00	1.00000E+00	1.51678E-04	6.64288E-02
4.00000E+00	-3.09944E-06	1.00000E+00	1.00000E+00	-1.22477E-04	8.71547E-03
4.50000E+00	-3.09944E-06	1.00000E+00	1.00000E+00	-3.12486E-04	-5.65881E-02
5.00000E+00	-3.09944E-06	1.00000E+00	1.00000E+00	-5.65200E-05	-7.23847E-02
5.50000E+00	-3.09944E-06	1.00000E+00	1.00000E+00	-1.05967E-04	-2.47982E-02
6.00000E+00	-3.09944E-06	1.00000E+00	1.00000E+00	-4.65325E-04	4.45340E-02
6.50000E+00	-3.21865E-06	1.00000E+00	1.00000E+00	-9.08231E-05	7.48319E-02
7.00000E+00	-3.33786E-06	1.00000E+00	1.00000E+00	3.59804E-05	3.95002E-02
7.50000E+00	-3.33786E-06	1.00000E+00	1.00000E+00	-6.08235E-05	-3.04319E-02
8.00000E+00	-3.33786E-06	1.00000E+00	1.00000E+00	-7.18786E-05	-7.37142E-02
8.50000E+00	-3.33786E-06	1.00000E+00	1.00000E+00	4.88555E-05	-5.23888E-02
9.00000E+00	-3.33786E-06	1.00000E+00	1.00000E+00	-1.46342E-04	1.47898E-02
9.50000E+00	-3.33786E-06	1.00000E+00	1.00000E+00	1.40902E-05	6.90467E-02
1.00000E+01	-3.33786E-06	1.00000E+00	1.00000E+00	1.82696E-05	6.28114E-02
1.05000E+01	-3.33786E-06	1.00000E+00	1.00000E+00	1.07115E-04	1.53397E-03
1.10000E+01	-3.33786E-06	1.00000E+00	1.00000E+00	-9.44130E-05	-6.11001E-02
1.15000E+01	-3.33786E-06	1.00000E+00	1.00000E+00	-1.41475E-06	-7.01992E-02
1.20000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	1.54379E-04	-1.78981E-02
1.25000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	1.81424E-04	5.00279E-02
1.30000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	8.00481E-05	7.42012E-02
1.35000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-4.23188E-05	3.33014E-02
1.40000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-3.69554E-05	-3.67547E-02
1.45000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-4.88530E-05	-7.46301E-02
1.50000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-1.78673E-04	-4.71717E-02
1.55000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	3.46627E-05	2.16022E-02
1.60000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	9.68023E-05	7.14621E-02
1.65000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	2.93238E-06	5.88076E-02
1.70000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-4.72559E-05	-5.05319E-03
1.75000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-3.43002E-04	-6.46639E-02
1.80000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-7.00681E-06	-6.75968E-02
1.85000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	4.97322E-05	-1.12181E-02
1.90000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	7.16317E-05	5.49837E-02
1.95000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	8.37785E-05	7.29679E-02
2.00000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	3.38018E-05	2.68944E-02
2.05000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	1.11363E-04	-4.25876E-02
2.10000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	7.52097E-05	-7.48880E-02
2.15000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	1.06968E-04	-4.15840E-02
2.20000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-7.34220E-05	2.80675E-02
2.25000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	1.37417E-04	7.31909E-02
2.30000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	1.77845E-06	5.44191E-02
2.35000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	2.99584E-05	-1.18873E-02
2.40000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-4.14707E-04	-6.77074E-02
2.45000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	3.63070E-04	-6.45468E-02
2.50000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	8.22138E-05	-5.09737E-03
2.55000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-4.42446E-05	5.88382E-02

**** SYSL/PC SIMULATOR OUTPUT -- 02-AUG-1994 11:54:41

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	ERROR	POS	CONT_POS	ACCEL	X
2.60000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-9.86569E-05	7.13421E-02
2.65000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-4.09178E-04	2.14158E-02
2.70000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	3.34387E-04	-4.72324E-02
2.75000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-2.48721E-05	-7.46281E-02
2.80000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-6.53588E-05	-3.68869E-02
2.85000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	1.34370E-04	3.32729E-02
2.90000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-2.80956E-04	7.41817E-02
2.95000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	-1.74434E-04	5.00682E-02
3.00000E+01	-3.45707E-06	1.00000E+00	1.00000E+00	1.18733E-04	-1.78684E-02

SIMULATION TIME = 66.681 SECONDS, UPDATE CALLS--327122, INTEGRATION STEPS-- 56
*** STRIP PLOTTING NOT AVAILABLE ***
*** STRIP PLOTTING NOT AVAILABLE ***
*** STRIP PLOTTING NOT AVAILABLE ***

GRAPH PREPARATION TIME = 0.001 SECONDS

```
*.....PROGRAM NAG1.DAT (STUDY CASE 4: GRIPPER AXIS)
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER

INTGER INIT_SEQ

INITIAL
      DELS=TSAMP
      INIT_SEQ=0
DYNAMIC
*
*-----DIGITAL PID CONTROLLER
*
      TARG_P1=STEP(0.1)
      TARG_POS=0.25*TARG_P1
*
NOSORT
      TEST=SAMPLE(0.0,FINTIM,TSAMP)
      IF(TEST.EQ.0.0) GO TO 10
*-----SEQUENCER(INITIALIZE ON FIRST PASS ONLY)
      IF(INIT_SEQ.EQ.1) GO TO 20
      INIT_SEQ=1
      INTG_PRE=0.0
      LAST_POS=0.0
      CONT_POS=POS
      CONT_SPD=0.0
      PRES_POS=POS
      TARG_PRE=TARG_POS
   20 CONTINUE
*-----PROFILE
      IF(TARG_POS.EQ.TARG_PRE) GO TO 50
      IF(TARG_POS.GT.TARG_PRE) CONT_SPD=MAX_SPD
      IF(TARG_POS.LT.TARG_PRE) CONT_SPD=-MAX_SPD
      TARG_PRE=TARG_POS
      PHASE=0.0
   50 CONTINUE
      IF(ABS(CONT_POS-TARG_POS).LE.3.0E-4) THEN
                                      PHASE=1.0
                                      CONT_SPD=0.0
                                      CONT_POS=TARG_POS
                                      ENDIF
      PRES_POS=POS
      CONT_POS=CONT_POS+CONT_SPD*TSAMP
*-----ERROR
      ERROR=CONT_POS-PRES_POS
*-----INTEGRATE
      INTG=INTG_PRE+PHASE*ERROR*IFACTOR/ISCALE
      INTG_PRE=INTG
      INTG_LIM=PHASE*LIMIT(-ILIMIT,ILIMIT,INTG)
*-----TACH
      SPEED=(PRES_POS-LAST_POS)/TSAMP
      LAST_POS=PRES_POS
*-----PROPORTION
      PROP=ERROR*PFACTOR/PSCALE
*-----DERIVE
      DERIV=SPEED*DFACTOR/DSCALE
*     PID
      VOLTAGE=LIMIT(-MAX_VOLT,MAX_VOLT,PROP+INTG_LIM-DERIV)
   10 CONTINUE
SORT
```

```
      E2=VOLTAGE-KB*OMEGA
      C1=REALPL(0.0,L/R,(1/R)*E2)
      C1_LIM=LIMIT(-MAX_CURR,MAX_CURR,C1)
      TM=KT*C1_LIM
      C2=TM-TL
      FORCE=K*POS
      TL=16*FORCE*KF
      OMEGA=REALPL(0.0,J/F,(1/F)*C2)
      THETA=INTGRL(0.0,OMEGA)
      POS=KF*THETA

PARAM IFACTOR=0.001, ISCALE=1.0, DFACTOR=.15, DSCALE=1.0,...
      PFACTOR=720.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=0.135,...
      MAX_VOLT=28, TSAMP=0.005,KB=0.034, L=1.2E-3, R=3.7,...
      MAX_CURR=1.0, KT=4.8,  F=6.589E-4, J=1.3E-4,...
      KF=1.9894E-4,K=40


INTEG RKM
TIMER DELT=0.0001, FINTIM=30.0, DELPR=1.0, DELGR=0.1
*PRINT ERROR,POS,C1_LIM,VOLTAGE,TL
*,INTG_LIM
PRINT CONT_POS,POS,ERROR,FORCE
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,FORCE,...
       VOLTAGE, INTG_LIM,SPEED,C1_LIM
*PLOTS STRIP,MODEL=97,IOPORT=97
PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
*GRAPH TIME, PHASE, TARG_POS, CONT_SPD
*GRAPH TIME, ERROR, POS, CONT_POS
*GRAPH TIME,C1_LIM,VOLTAGE,INTG_LIM
GRAPH TIME, FORCE
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),...
      C1_LIM(AMPERE),VOLTAGE(VOLT),SPEED(INCH/SECOND),...
      FORCE(LB)
END
STOP
```

```
                    **** SYSL/PC SIMULATION DATA ****
TITLE NASA ROBOT CONTROL SYSTEM
TITLE WITH SAMPLED-DATA PIR CONTROLLER
PARAM IFACTOR=0.001, ISCALE=1.0, DFACTOR=.15, DSCALE=1.0,...
      PFACTOR=720.0, PSCALE=1.0, ILIMIT=100.0, MAX_SPD=0.135,...
      MAX_VOLT=28, TSAMP=0.005,KB=0.034, L=1.2E-3, R=3.7,...
      MAX_CURR=1.0, KT=4.8,  F=6.589E-4, J=1.3E-4,...
      KF=1.9894E-4,K=40
INTEG RKM
TIMER DELT=0.0001, FINTIM=30.0, DELPR=1.0, DELGR=0.1
PRINT CONT_POS,POS,ERROR,FORCE
PREPAR TARG_POS, CONT_POS, PHASE, CONT_SPD, POS, ERROR,FORCE,...
        VOLTAGE, INTG_LIM,SPEED,C1_LIM
PLOTS STRIP,MODEL=64,IOPORT=0,LINES=3
GRAPH TIME, FORCE
UNITS TIME(SECOND),TARG_POS(INCH),CONT_POS(INCH),...
      CONT_SPD(INCH/SECOND),POS(INCH),ERROR(INCH),...
      C1_LIM(AMPERE),VOLTAGE(VOLT),SPEED(INCH/SECOND),...
      FORCE(LB)
END
```

**** SYSL/PC SIMULATOR OUTPUT -- 10-AUG-1994 11:26:30

NASA ROBOT CONTROL SYSTEM
WITH SAMPLED-DATA PIR CONTROLLER

TIME	CONT_POS	POS	ERROR	FORCE
0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01	0.00000E-01
1.00000E+00	1.22175E-01	9.02186E-02	3.19565E-02	3.60874E+00
2.00000E+00	2.50000E-01	2.23919E-01	2.60843E-02	8.95674E+00
3.00000E+00	2.50000E-01	2.49595E-01	4.04552E-04	9.98382E+00
4.00000E+00	2.50000E-01	2.49963E-01	3.73274E-05	9.99851E+00
5.00000E+00	2.50000E-01	2.49966E-01	3.35127E-05	9.99866E+00
6.00000E+00	2.50000E-01	2.49967E-01	3.34382E-05	9.99866E+00
7.00000E+00	2.50000E-01	2.49967E-01	3.33637E-05	9.99867E+00
8.00000E+00	2.50000E-01	2.49967E-01	3.32743E-05	9.99867E+00
9.00000E+00	2.50000E-01	2.49967E-01	3.32445E-05	9.99867E+00
1.00000E+01	2.50000E-01	2.49967E-01	3.32147E-05	9.99867E+00
1.10000E+01	2.50000E-01	2.49967E-01	3.32147E-05	9.99867E+00
1.20000E+01	2.50000E-01	2.49967E-01	3.31998E-05	9.99867E+00
1.30000E+01	2.50000E-01	2.49967E-01	3.31700E-05	9.99867E+00
1.40000E+01	2.50000E-01	2.49967E-01	3.31253E-05	9.99868E+00
1.50000E+01	2.50000E-01	2.49967E-01	3.30806E-05	9.99868E+00
1.60000E+01	2.50000E-01	2.49967E-01	3.30508E-05	9.99868E+00
1.70000E+01	2.50000E-01	2.49967E-01	3.30210E-05	9.99868E+00
1.80000E+01	2.50000E-01	2.49967E-01	3.29763E-05	9.99868E+00
1.90000E+01	2.50000E-01	2.49967E-01	3.29465E-05	9.99868E+00
2.00000E+01	2.50000E-01	2.49967E-01	3.29465E-05	9.99868E+00
2.10000E+01	2.50000E-01	2.49967E-01	3.29465E-05	9.99868E+00
2.20000E+01	2.50000E-01	2.49967E-01	3.29465E-05	9.99868E+00
2.30000E+01	2.50000E-01	2.49967E-01	3.29465E-05	9.99868E+00
2.40000E+01	2.50000E-01	2.49967E-01	3.29465E-05	9.99868E+00
2.50000E+01	2.50000E-01	2.49967E-01	3.29316E-05	9.99868E+00
2.60000E+01	2.50000E-01	2.49967E-01	3.29018E-05	9.99868E+00
2.70000E+01	2.50000E-01	2.49967E-01	3.29018E-05	9.99868E+00
2.80000E+01	2.50000E-01	2.49967E-01	3.29018E-05	9.99868E+00
2.90000E+01	2.50000E-01	2.49967E-01	3.28869E-05	9.99868E+00
3.00000E+01	2.50000E-01	2.49967E-01	3.28571E-05	9.99869E+00

SIMULATION TIME = 22.850 SECONDS, UPDATE CALLS--142068, INTEGRATION STEPS-- 24
*** STRIP PLOTTING NOT AVAILABLE ***

GRAPH PREPARATION TIME =86400.000 SECONDS